Contractor Report 2005-04

Terrain Analysis for Human–Robot Interaction (TAH–RI): Enabling Terrain Understanding to Improve Tactical Behavior

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20050620 142

April 2005

United States Army Research Institute for the Behavioral and Social Sciences

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REPORT DOCUMENTATION PAGE

1. REPORT DATE (dd-mm-yy)	2. REPORT TYPE	3. DATES COVERED (from. . . to)
April 2005	Final	August 2004 – February 2005

4. TITLE AND SUBTITLE	5a. CONTRACT OR GRANT NUMBER
Terrain Analysis for Human–Robot Interaction (TAH–RI): Enabling Terrain Understanding to Improve Tactical Behavior	W74V8H-04-P-0482
	5b. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)	5c. PROJECT NUMBER
James Hicinbothom (CHI Systems, Inc.), Robin Murphy (University of Southern Florida), Dawn Riddle and Ken Graves (CHI Systems, Inc.)	861
	5d. TASK NUMBER
	5e. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
CHI Systems, Inc. 1035 Virginia Drive, Suite 300 Fort Washington, PA 19034	04018.050208

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. MONITOR ACRONYM
U. S. Army Research Institute for the Behavioral & Social Sciences 2511 Jefferson Davis Highway Arlington, VA 22202-3926	ARI
	11. MONITOR REPORT NUMBER Contractor Report 2005-04

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTE
This report is published to meet legal and contractual requirements and may not meet ARI's scientific or professional standards for publication.

14. ABSTRACT *(Maximum 200 words)*:
Terrain has a big impact on how battlefield situations unfold primarily because of its effects on observability, mobility, and restriction of fields of fire. As armed forces of the information age come within each other's sensor coverage, information about them is rapidly conveyed to their opponents. Terrain imposes constraints and opens opportunities for the creative use of Battlefield Operating Systems (BOS) and the capabilities and limitations of available troops, vehicles, systems, and materiel. Thus, understanding terrain, and its tactical import is essential for a force to succeed in its missions. Future Force Warrior (FFW) and Future Combat Systems (FCS) initiatives are developing advanced functional capabilities to aid Soldiers in operations to control and hold ground. Adding robotic vehicles, sensors, and weapons creates a planning and coordination challenge for commanders, and highlights the need for autonomous robotic systems that effectively "understand" the tactical import of terrain and integrate that understanding into their situation awareness and behavior-generation processes. TAH-RI is reusable component software providing means of increasing readiness of Soldiers (e.g., in training and performance support systems) to integrate terrain understanding into battlefield decision-making processes, and means of enabling more autonomy in robots through terrain understanding for tactical behavior generation.

15. SUBJECT TERMS: Autonomous Agents, Robotics, Multiagent Planning, Autonomous Navigation, Autonomous Vehicles, Intelligence preparation of the battlefield, Terrain, Military Operations, Military Tactics,

SECURITY CLASSIFICATION OF			19. LIMITATION OF ABSTRACT	20. NUMBER OF PAGES	21. RESPONSIBLE PERSON
16. REPORT	17. ABSTRACT	18. THIS PAGE			
Unclasified	Unclasified	Unclassified	Unlimited		Ellen Kinzer Technical Publication Specialist 703-602-8047

TERRAIN ANALYSIS FOR HUMAN–ROBOT INTERACTION (TAH–RI): ENABLING TERRAIN UNDERSTANDING TO IMPROVE TACTICAL BEHAVIOR

EXECUTIVE SUMMARY

In this feasibility study, we investigated implications of the fact that military decision-making for ground forces is driven by tactical constraints and opportunities based, in large part, on terrain. Future Force Warrior (FFW) and Future Combat Systems (FCS) initiatives are developing advanced functional capabilities to aid Soldiers in operations to control and hold ground. Adding robotic vehicles, sensors, and weapons creates a planning and coordination challenge for commanders, and highlights the need for autonomous robotic systems that effectively "understand" the tactical import of terrain and integrate that understanding into their situation awareness and behavior-generation processes. Means of increasing readiness of Soldiers (e.g., through training and performance support) to properly integrate terrain understanding into their own battlefield decision-making processes are needed, as are means of enabling more autonomy in robots through terrain understanding for tactical behavior generation.

Procedure

In this study, we assessed terrain analysis capabilities of existing digital tools to help determine if, and how, output from these tools could be utilized as inputs for training humans, aiding humans during operations, and informing intelligent agents and autonomous robots of tactically important terrain features. Analyzed means of integrating terrain analysis data, intelligence data, and the Common Relevant Operating Picture (CROP) to aid path planning and execution. Also analyzed means of representing and reasoning about commander's intent and mixed-initiative battlefield communications among combinations of humans and robots. Completed initial design of composable software architecture enabling rapid integration into existing digital C2 systems, Intelligent Tutoring Systems, and advanced robots.

Findings

Existing digital tools for aiding and training humans are inadequate and must be improved. Technology to better enable humans, and especially robots, to effectively understand terrain and its tactical import is needed. Highlighting areas of terrain onscreen can help a human Soldier, but an autonomous robot or an Intelligent Tutoring System (ITS) needs a means to efficiently represent and reason about what is being highlighted for a human to see. A novel Terrain Analysis for Human-Robot Interaction (TAH-RI) software sub-assembly was designed to solve this problem, based on state-of-the-art terrain analysis algorithms, intelligent agent software, and other technologies developed to aid FCS and FFW. Importantly, TAH-RI incorporates terrain analysis tools that are the next generation of CHI Systems' software components fielded in the Marine Corps' Command and Control Personal Computer (C2PC).

Utilization of Findings

Build TAH-RI sub-assembly and demonstrate its utility for enhancing existing tools.

TERRAIN ANALYSIS FOR HUMAN–ROBOT INTERACTION (TAH–RI): ENABLING TERRAIN UNDERSTANDING TO IMPROVE TACTICAL BEHAVIOR

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Introduction

Terrain has a big impact on how battlefield situations unfold primarily because of its effects on intervisibility, mobility, and restriction of fields of fire. As armed forces of the information age come within each other's sensor coverage, information about them is rapidly conveyed to their opponents. Terrain can play a significant role in determining their effective sensor coverage area. Terrain and ground cover also can play a significant role in constraining, to varying degrees, mobility of vehicles and dismounted infantry and scouts. Terrain also can constrain engagability by restricting possible fields of fire for Line of Sight (LOS), Extended LOS (ELOS), Non-LOS (NLOS), and Beyond LOS (BLOS) weapons systems. Thus, understanding the terrain of the battlespace, and its tactical import for military operations is essential if a force is to succeed in its missions. This is why understanding the terrain comes immediately after the mission and the enemy in the US Army Training and Doctrine Command (TRADOC) guidance to commanders to approach battlefield decision-making by considering the Mission, Enemy, Terrain, Troops, and Time (METT-T). Terrain imposes constraints and opens opportunities for the creative use of Battlefield Operating Systems (BOS) and the capabilities and limitations of available troops, vehicles, systems, and materiel.

Understanding the impact of terrain on plans and actions can be hard for people. This is true in both military and civilian endeavors, although the training that comes with military service certainly can help in this regard. Integrating terrain understanding with plans to achieve both shared and individual goals can lead to less than optimal results (e.g., as with buddies out hunting who get lost or separated), as illustrated in the humorous writings of Patrick McManus:

> *"Every hunter knows what a rendezvous is. That's where one hunter says to another, 'Al, you take that side of the draw and I'll take this one and we'll meet in twenty minutes at the top of the hill.' The next time they see each other is at a PTA meeting five years later in Pocatello. That's a rendezvous.*
>
> *It is simply against the basic nature of hunters to arrive at a designated point at a designated time. If one of my hunting pals said, 'I'll meet you on the other side of this tree in ten seconds,' one of us would be an hour late. And have the wrong tree besides."* [McManus, 1981, p.174]

In most cases, however, these problems can have much more serious results. On the battlefield, the results can be tragic and of historic proportions, as in the Civil War at the battle of Gettysburg where not every commander present on those fateful days truly understood the potential impact of the terrain of that battlefield on their plans and intended actions (cf., Shaara, 1975). Better means of training people to understand the tactical import of terrain are needed. Better means of performance support for people with a lot more than a deer on their mind are needed to help properly factor terrain into on-going activities and plans. Similarly, means of enabling the Army's envisioned robotic systems to understand terrain and its tactical import (e.g., to be able to represent and reason about METT-T in an efficient yet effective way) is

essential to their future battlefield utility. If properly understanding terrain import is hard for people, imagine the difficulties encountered by autonomous robots in performing this feat!

Purpose and Organization of the Report

This technical report is the Final Report for the Terrain Analysis for Human-Robot Interaction (TAH-RI) Phase I STTR effort for contract number W74V8H-04-P-0482, CDRL 0002 and covers the period of performance for Phase I, from 7 August 2004 through 7 February 2005. The research reported here focused on designing and assessing feasibility of a solution to the terrain understanding problem, called Terrain Analysis for Human-Robot Interaction (TAH-RI), a novel software sub-assembly which can be integrated into a variety of systems:

- to enable more effective solutions for Soldiers through
  - training systems and Intelligent Tutoring Systems,
  - decision aiding subsystems, and
  - performance support systems
- to enhance autonomy and utility of tactical robotic systems by enabling
  - terrain analysis,
  - more effective representations of analytic results,
  - integration of those results with CROP and Intelligence, and
  - much more efficient human-robot interaction is also needed
    - with unit commanders
    - with command post staff or other Soldiers tasked with using robots
    - with other Soldiers fighting near robots
    - with (apparent) non-combatants near robots.

Details of the work completed in Phase I, and the insights gained into feasibility of achieving the stated goals for TAH-RI in Phase II development and evaluation, are described in this report.

Background

As the transformation of the Armed Forces of the United States unfolds, the importance of enabling our Soldiers to shape the battle before coming in contact with the enemy is significantly increasing. This is especially true for the smallest units (e.g., traditional platoons and squads, teams and cells, scouts and individual Future Force Warriors) which must be able to achieve enhanced lethality, survivability, tactical awareness, mobility, sustainability, training and readiness to overcome both traditional and asymmetric threats as the information age shapes the battlespace of the 21st century. Meeting these challenges is becoming more viable as innovative new capabilities for the Future Force Warrior (FFW) and Future Combat System of Systems (FCS) are rolled out. However, significant challenges remain.

One of the remaining critical challenges to ensuring realization of this potential for shaping the battle well before contact is the integration of terrain understanding with a Common Relevant Operations Picture (CROP) enabling Soldiers to understand the battlefield situation and the tactical importance of the terrain across which the battle is unfolding, especially on complex or urban terrain. Building and maintaining situation awareness of the relevant areas and features of the battlespace is vital to effective and efficient employment of the Future Force's technical

advantages over conventional and asymmetric forces. Many Soldiers develop significant expertise in performing this integration on-the-move with available information – but not all Soldiers develop this level of competence. Thus, intelligent software-driven Electronic Performance Support Systems (EPSSs), or Decision Aids (DAs), and Intelligent Tutoring Systems (ITSs) are needed to ensure that all of the human warfighters in these units can effectively and efficiently employ all of these advanced capabilities to achieve victory on the future battlefield. Of special interest is the envisioned integration of a variety of robotic vehicles, sensors, weapons systems, and other kinds of robotic systems intended to aid lower-echelon commanders "at the pointy end of the stick" to master the battlespace, even when the terrain turns from open and rolling to complex and urban.

If the problem of understanding the unfolding situation is critical and difficult for human combatants, it is even more so for the envisioned robotic combatants and support systems. Robotic systems will be participating in armed conflicts in the coming decades, but will they enhance or degrade the abilities of the human warfighters beside them and of their commanders? While holding out the promise of significantly enhancing a commander's ability to build and maintain an accurate CROP, robotic sensor systems also threaten to sap a commanders' attention given current robotic technologies inability to achieve autonomy. Rather than dramatically increasing a human commander's span of control with not only more "troops" but more "dumb" troops, robotic systems need to be "smart" enough, robust enough, and autonomous enough to minimize impact on the forces with which they are fielded. To be effectively (and efficiently) autonomous, these robotic systems must interact with their human commanders and the major Battlefield Operating Systems (BOS) in which they play vital roles, and must have access to relevant data, information, analysis tools, and results of analyses. Whether engaged in combat, combat support, or combat service support, each of these robotic systems must "understand" and act upon their commander's intent, their mission and specific objectives, and the battlefield environment. Obviously, an armed robotic scout will need both significant autonomy to move about the battlespace to achieve needed sensor (and possibly weapons) coverage while still requiring significant human oversight and control of the robot's weapon(s).

Understanding the battlefield environment also involves more than just "knowing" your location, more than just finding a navigable route over the relevant terrain to reach specified waypoints. Rather, it involves some level of "knowing", integrating, maintaining, and effectively using their whole CROP, including relevant intelligence information and assessments, relevant operations information and plans, and the tactical importance of the terrain in their area of operations and area of interest. Autonomous robotic systems need to build and maintain, and then act upon, their own awareness of the battlefield situation (recent past, current, and projected future). These systems need to be able to at least read and use the products of the Intelligence Preparation of the Battlefield (IPB) incorporated within the mission and orders they've received, and integrate their own local knowledge with this larger picture. Some of these systems will even be essential participants in the production and on-going maintenance/revision of the data and information contained in those IPB products. These needs also apply to the intelligent software required to enable effective intelligent Decision Aiding (DA) and Intelligent Tutoring Systems (ITSs) to aid and train the human warfighters in building, maintaining, and using their own understanding of the CROP and battlespace terrain.

Another important aspect of this set of problems is more directly in the area of human-robot interaction. Because of the significant differences between human beings vs. robotic systems as subordinates, humans controlling robotic systems can be surprised by the unexpected

kinds of errors, mistakes, misunderstandings, and failures that can occur. Thus, in addition to formulating and following this guidance, robotic systems also must be able to explain what they are doing or intend to do, when they intend to do it, and why they are doing it at this time and place given the current circumstances and its understanding of those circumstances.

Importance of Autonomy for Robotic Systems

For robotic systems, a key challenge is acquiring, understanding, and integrating disparate elements of information describing the total battlespace, including terrain effects on operations planning and execution. This includes integration of physical environment and topography information with the current and anticipated distribution of forces across the battlespace available through operations status reports and plans (primarily about own forces) and intelligence analyses and reports (primarily about opposing forces). For human warfighters, viewing a topographic map overlaid with unit symbols, targets, maneuver graphics, and other assorted information renderings can sometimes be sufficient to enable cooperative work to achieve a given unit's mission. For robots, it's a little bit harder.

As FCS and FFW weapon systems approach fielding, including robotic missile, gun, sensor, reconnaissance, logistics, and search and rescue systems, the human Soldiers who must command and control these robotic systems will be faced with an extremely difficult span of control problem. Other human Soldiers who depend upon these autonomous robotic systems to fulfill various combat, combat support, and combat service support functions will also be faced with a significant situation awareness and human-computer interaction problem, because these systems will often not behave in human-like ways and will have very different capabilities and limitations than their human counterparts.

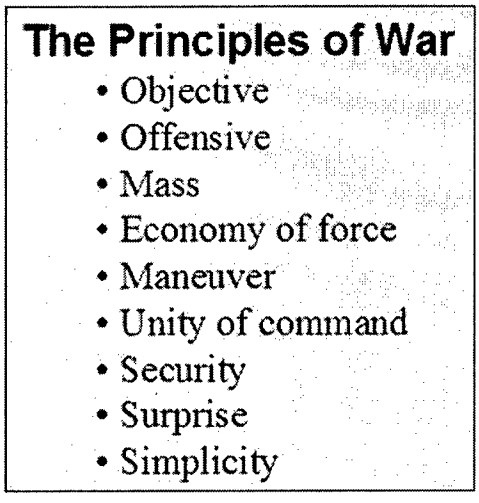
As an example, the span of control problem for human warfighters was amply demonstrated in the May 2001 Future Combat Command and Control (FCC2) experiment at the Mounted Maneuver Battlespace Lab (MMBL). During this experiment, in which CHI Systems participated, a typical FCS-equipped Cell (i.e., platoon) was composed of a single command and control vehicle with three personnel, one of which was a driver, two robotic reconnaissance vehicles, two robotic multi-role guns, a robotic mortar, robotic missile launcher vehicle, and a robotic uninhabited aerial reconnaissance platform (UAV). Additionally, the robotic reconnaissance vehicles could deploy up to 40 uninhabited ground sensors (UGS). Typically, a cell leader was required to command and control up to 45 robotic vehicles and sensors, all of which required individual attention in order to cause the systems to perform various functions in a timely fashion to achieve overall unit objectives. CHI Systems' observation of the FCS cell leaders and their assistants revealed that they were essentially overwhelmed by the need to control the numerous robotic systems at their command. This occurred when two personnel were attempting to control the robotic systems; however, during continuous operations, when only one human controller was available, even this limited ability to control the robotic systems was degraded to the point where control was completely ineffective. During the course of a prior project, one of CHI Systems' personnel attempted to control the various robotic vehicles of an FCS cell on numerous occasions, with similar results. It was literally impossible to maintain awareness of all the robotic systems.

Another example of the need for robust autonomy in terrain interpretation in robotic systems occurred during the recent DARPA Grand Challenge competition in March 2004. As reported at the outbriefing at the DARPA/DSRC Workshop on Hardware Fabric on Intelligent Machines immediately following the competition, one of the larger competing robotic vehicles

kicked up significant debris and boulders onto the road. An entry that followed later relied primarily on the previous model of the road and surrounding terrain. As a result, the vehicle expected an uncluttered surface and attempted to navigate at a higher speed than was safe for the rapid reactive turns required to avoid the rocks. Because it was not programmed to understand the actual terrain, the vehicle could not adapt and quickly failed. This example illustrates that a realistic robotic terrain interpretation system must rely on both top-down terrain modeling (a priori maps) and bottom-up (situated learning) to be aware of the terrain and make the appropriate decisions.

Importance of Terrain for Military Operations

Terrain can significantly affect application of each of the 9 principals of war, and understanding of terrain, or lack thereof, may be the difference between victory and defeat. The potential impact on each principle is summarized below:



- Objective: A clear objective is required in order to achieve the mission; lack of understanding of the terrain may mean the desired objective is unattainable.
- Offensive: Offensive action wins battles; lack of understanding of terrain may inhibit the ability to remain on the offensive as units bog down.
- Mass: Massing combat power at the critical place and time is key; lack of understanding of terrain may lead to inability to mass.
- Maneuver: Allows forces to mass and disperse as needed to keep the initiative; lack of understanding of terrain slows maneuver and risks loss of the initiative.
- Economy of Force: Risk must be accepted in some areas in order to mass combat power; Terrain is one of the key factors in economy of force operations and lack of terrain understanding leads to unacceptable risk.
- Unity of Command: A single commander directs the force toward the common objective; failure to understand terrain may not allow the commander to position so as to achieve unity.
- Security: Security protects combat power; not understanding the terrain degrades security in terms of observation, fields of fire, etc.
- Surprise: Surprise is a combat multiplier; failure to understand terrain may lead to premature discovery of forces attempting surprise.
- Simplicity: Plans and orders must be simple and direct; failure to understand terrain may cause seemingly simple plans to become complicated during execution.

How are Terrain Analysis Tools Used Now?

- Intelligence Preparation of the Battlefield (IPB).
  - Analysis of the terrain and terrain effects to support the generation and wargaming of friendly and enemy courses of action.

- Situational Templates apply terrain effects to predict likely enemy locations.
- Mobility Corridors to identify Avenues of Approach.
- Mobility and Combined Obstacle Overlays
- Foundation for IPB Event and Decision Support templates in COA wargaming.
- IPB wizard built by CHI Systems currently fielded with USMC in C2PC application, as shown in Figure 1, below. IPB Wizard uses our terrain component to walk user through IPB process and provides html-based document that is used as part of intelligence annex to operations order.

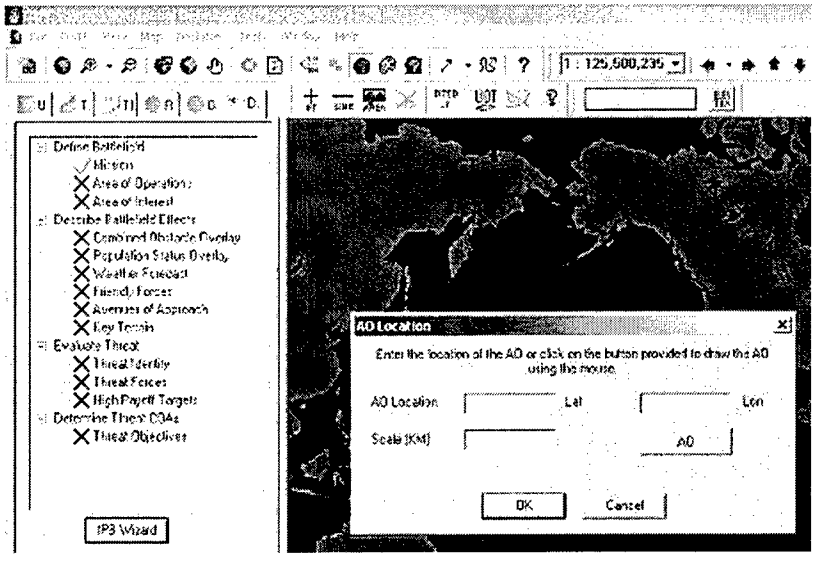


Figure 1. IPB Wizard in USMC's C2PC

- Route Planning (fastest route, covered and concealed routes)
- Time-based Mobility Range Rings
- Identification of Restricted, Severely Restricted, Unrestricted mobility areas
- Identification of mobility corridors for different tactical echelons
- Line of Sight for optical sensors and weapon systems
- Aerial Line of Sight
- Elevation profiles
- Elevation contour maps
- Sensor location planning
- UAV flight route planning
- Flight path planning and evaluation for Non-Line-of-Sight Launch System (NLOS-LS) Precision Attack Missile.
- Terrain Macros
  - Likely helicopter landing zones
  - Likely artillery firing positions
  - Likely choke points (Named and Targeted Areas of Interest (NAI & TAI)
  - Likely and known bridging sites

Examples of how people use terrain analyses with current state-of-the-art terrain analysis algorithms are shown in Figure 2, below. Furthermore, terrain (and its effects) directly affect almost every step in the military decision-making process (illustrated in Figure 3).

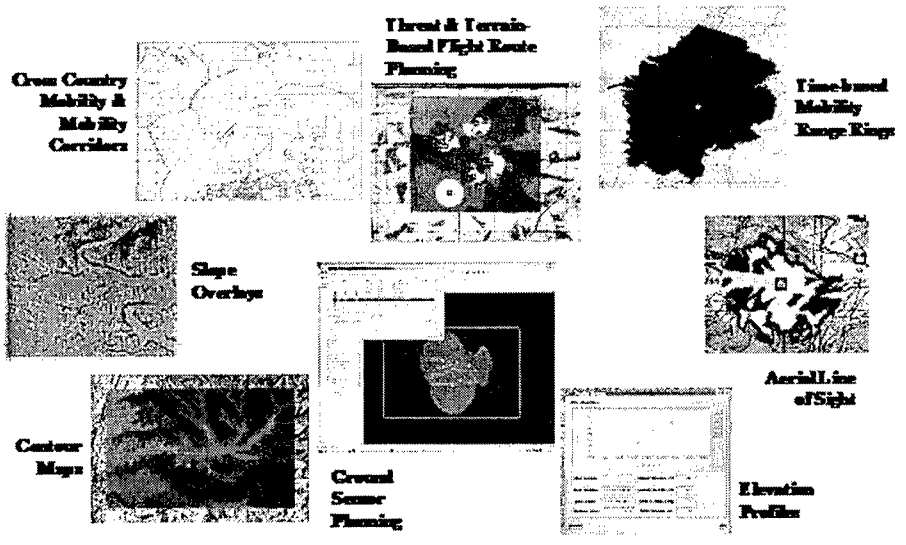


Figure 2. Examples of Terrain Analyses for a Variety of Uses (Human-Readable)

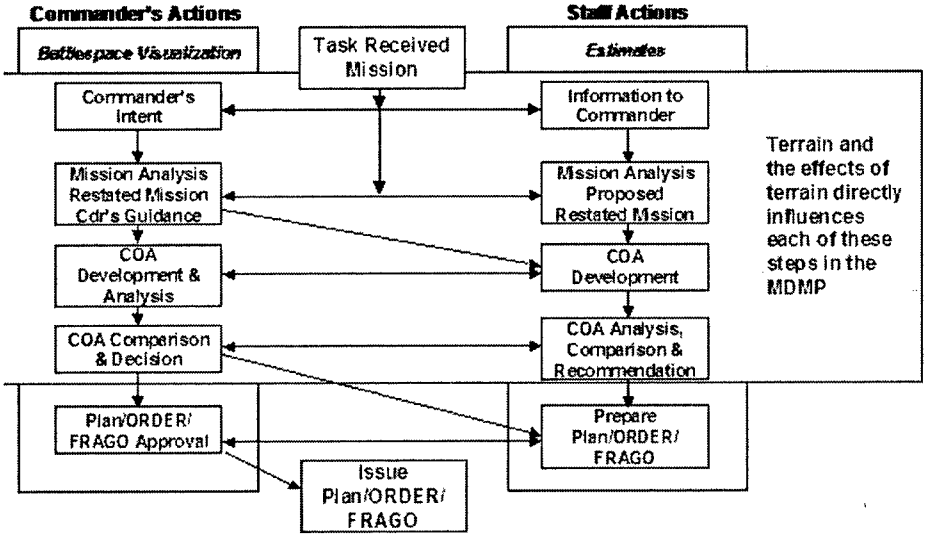


Figure 3. Importance of Terrain in the Military Decision-Making Process

Project Overview

The overall STTR program objective for Phase I (i.e., feasibility assessment and conceptual design) and Phase II (i.e., detailed design and development) is to enable human decision makers, intelligent software agent intermediaries (i.e., disembodied robots), and autonomous robotic systems to effectively and efficiently use terrain analysis results to enhance

battlefield decision-making. Specifically, for this 6-month Phase I effort, our objective is stated below.

Military decision-making for ground forces is driven in large part by tactical constraints and opportunities based on terrain. The US Army's Future Force Warrior (FFW) and Future Combat Systems (FCS) programs are developing advanced functional capabilities to greatly increase effective combat power of our warriors on land. However, despite significant technological advances, Soldiers still have to take, hold, and defend tactically significant terrain. Adding robotic vehicles, sensors, and weapons systems helps in some ways, but also can create a planning and coordination challenge for the human commander. The addition of these kinds of systems also means that analyses results needed for effective decision-making must be in a form useful for enabling 'understanding' by robots as well as humans. Coordinating all these assets is not easy, even at the FCS Cell level. Terrain Analysis for Human-Robot Interaction (TAH-RI) is intended to ensure that any human or robot who needs to understand the integrated tactical importance of terrain, intelligence, and CROP (Common Relevant Operating Picture) can understand it, along with the commander's intent. The overall goal is to bridge the remaining critical gaps between current state-of-the-art tools in terrain analysis/reasoning and the operational needs of the warfighter in using these tools for command and control of forces that include varying combinations of robotic and non-robotic force elements. Based on a review and assessment of technology status and mission and task requirements, we will design and demonstrate a TAH-RI system solution that will address all of the relevant implementation and performance issues.

Phase I Work Summary

The specific tasks performed in Phase I are summarized below.

Task 1: Assess Terrain Analysis Capabilities and Unmet Needs

Assess terrain analysis capabilities of existing digital tools and determine if/how output from these tools can be utilized as inputs for training humans, aiding humans during operations, and informing intelligent agents and autonomous robots.

Task 2: Determine What Tool Design Changes Needed

Determine what design changes will be needed in selected application systems to enable integration of TAH-RI as a sub-assembly suitable for guiding humans and robots in understanding and utilizing the tactical significance of specific terrain.

Task 3: Investigate Use of Commander's Mission Intent

Investigate capture of commander's mission intent for maneuver into computer readable-format, so that it can be used in the TAH-RI system. This will include the development of a graphical user interface to help enter mission details.

CHI Systems has significant experience with this problem and with a variety of partial solutions that have been attempted in the past. Truly solving this problem requires a mixture of old and new approaches. Requirements of and design for this GUI are being refined and documented.

Task 4: Assess How to Integrate CROP with Robots

Assess how to integrate terrain analysis data, intelligence data, and the operating picture to assist path planning and execution.

Task 5: Determine What Mixed-Initiative Communications are Required

Determine what mixed-initiative communications are required to guide route planning and execution. Communications could be between human and intelligent agent, human and robot, or intelligent agent and robot. How to communicate priorities and constraints will be determined.

Task 6: Assess Requirements for Real-Time User-Updatable Database(s)

Assess the requirements for a real-time user-updatable database(s) of terrain information and analysis results.

Task 7: Complete the TAH-RI Architecture

Complete the TAH-RI architecture, combining reusable component software, adaptive cognitive agents, and state-of-the-art robotic protocols. Goal is to create an architecture that can be integrated with a host application (such as an existing digital command and control system).

Task 8: Document Progress and Report Results

Document progress and report results through monthly status reports and through final report documenting Phase I results and their import for assessing feasibility of Phase II/III development and fielding of TAH-RI.

The results achieved in performance of the Phase I work are discussed below, by task.

Task 1 Results : Assess Terrain Analysis Capabilities and Unmet Needs.

Our assessment of key existing systems' capabilities resulted in identification of a number of unmet needs. We discuss these results below, focusing especially on the key issues of terrain-sensitive path planning and the broader issues of navigation and means of enabling robotic systems to integrate and understand the spatial representation of threats, terrain, own forces, and some of the many other factors necessary to fully understand METT-T. Many of these latter issues are discussed in more detail further below with results of Tasks 2 and 4.

Existing Digital C2 Systems and Simulation Environments.

The principal digital command and control systems for land warfare (e.g., at Echelons Brigade and Below) currently available are the Army's Force XXI Battle Command Brigade and Below (FBCB2) and the Marine Corps' Command and Control Personal Computer (C2PC). Each of these systems provide some level of terrain analysis capability to its users. These capabilities, and those of the ONESAF Test Bed (OTB) simulation environment, were analyzed to help determine what terrain analysis needs remain unmet by available digital tools.

During Phase I, the CHI team analyzed existing digital tools' (e.g., FBCB2, C2PC, OTB) terrain analysis capabilities, using available information. These digital tools were assessed in terms of their terrain analysis capabilities' utility for training humans, aiding humans during on-going operations, and informing intelligent agents and autonomous robots regarding terrain implications for current and anticipated possible courses of action by friend and foe. Work on this task involved using CHI Systems' experience with developing software components for the

USMC's C2PC, and our experience in working with OTB-SAF and in developing a variety of training and intelligent tutoring systems. Additionally, our in-house expertise on terrain analysis and its use in battlefield planning and command and control (C2) was used to identify unmet needs. Dr. Robin Murphy's robotics expertise significantly enhanced our team's investigation of the issues of integrating terrain analysis capabilities with existing and future robotic systems.

Terrain-Sensitive Path Planning

Terrain-sensitive path planning is an emerging area of concern within the general domain of path planning. Path planning is just one of four major functions necessary for robot navigation. While this project focuses on metric path planning, it is helpful to have an overview of navigation and path planning in general before discussing the state of the art in terrain-sensitive path planning and path planning for teams of mobile robots.

Additionally, our team completed selection of algorithms to be used in TAH-RI, and even implementation and integration of one of those algorithms: TRULLA. This work is informed by our review of literature of algorithms for real-time terrain interpretation from sensor data, robot systems which use terrain interpretation from maps to plan and navigate, and methods of comparing real-time terrain interpretation with predicted terrain. Toward this end, our team refined a set of preliminary traversability map file format requirements (i.e., the format for sharing the data needed by wavefront propagation style terrain analysis algorithms like TRULLA). Implementation of TRULLA on the physical robot selected for Phase I development completed using the latest version of this traversability map file format. An illustration showing the resulting field produced by the TRULLA algorithm is illustrated in Figure 4, below.

Navigation Overview

Following (Murphy, 2000), robot navigation can be divided into four questions, each producing a distinct set of algorithms: *where am I going?* (mission planning); *what's the best way there?* (path planning); *where have I been?* (mapping or exploration); and *where am I?* (localization). Note that tactical navigation, "ooops, better avoid this obstacle," is considered an execution control issue, not a navigational issue. Path planning is distinct from the other three functions. Mission and path planning can be considered knowledge-based activities, while mapping and localization are sensor-based activities. Mission planning concerns determining goals and constraints which can then be processed by the path planner; for example that Robot 1 should go to Location A and rendezvous with Robot 2 by Time T. As will be seen in the following sections, path planning relies on maps to compute the path (usually as a set of waypoints) based on the mission goals and constraints. Therefore, mission and path planning use algorithms and approaches operating over knowledge about the situation. In contrast to mission and path planning, mapping and localization are generative functions, where at each step the agent is interpreting sensor data.

Path Planning Synopsis

Path planning algorithms for unmanned ground vehicles has been explored since the late 1960's. Approaches fall into two categories: *topological* and *metric*. Topological methods are also known as "route" or "landmark" navigation and use topological maps or perceptual associations to direct the robot to a goal. The paths produced are usually tuples of *<next_landmark, movement_strategy>*. Topological methods do not guarantee optimality and over the years, their primary use has been for route retracing. In addition, they require a projection of what the robot would see along the desired route; projecting perception from map

data to the degree of accuracy needed remains an open question. As a result, this project does not consider topological methods. Metric methods rely on maps and usually produce a path that is optimal according to some criteria, usually distance. The paths produced are usually lists of waypoints, most often in GPS coordinates. The waypoints do not necessarily correspond to a perceivable landmark (e.g., intersection of roads).

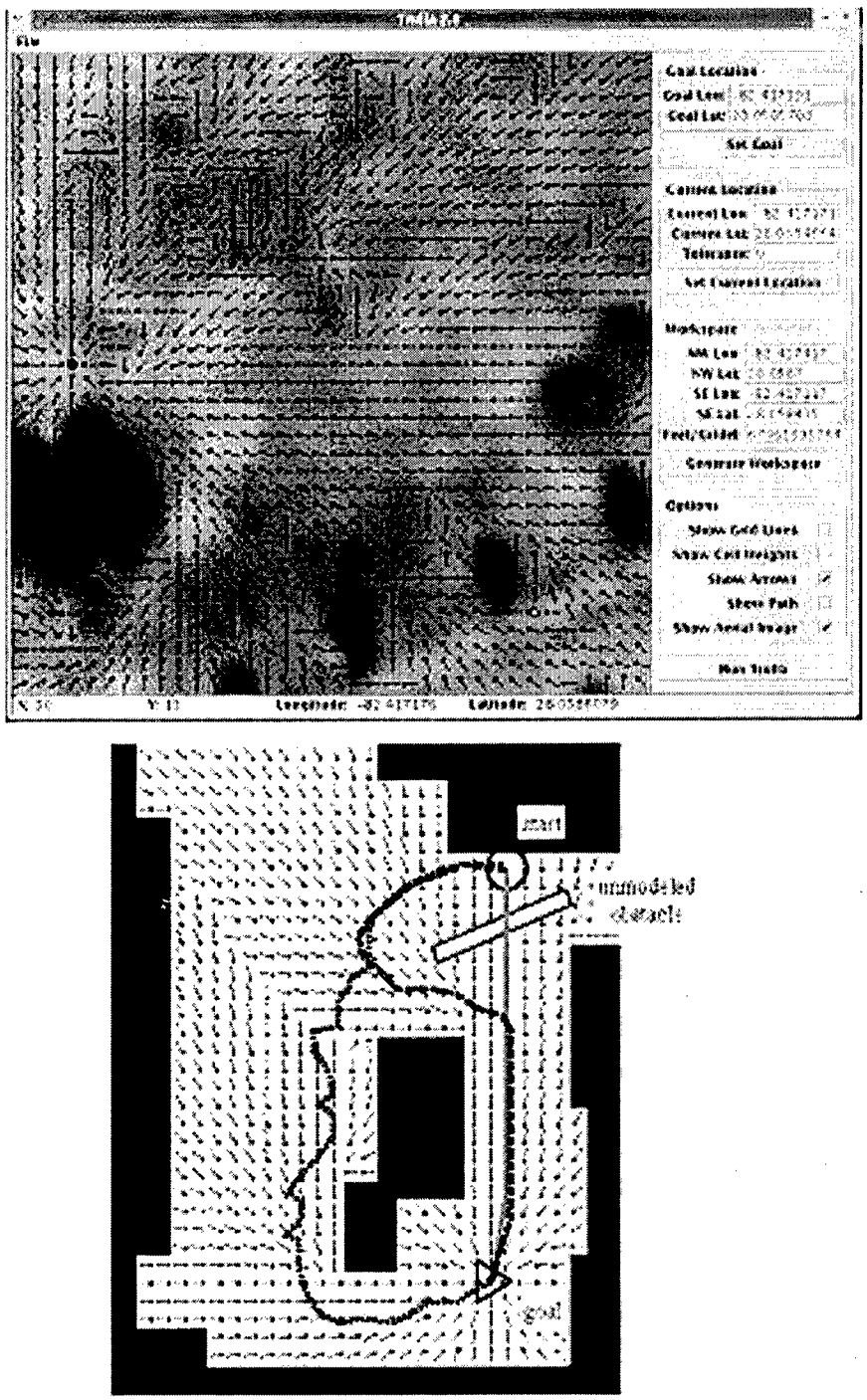


Figure 4. TRULLA Wavefront Path Planning Algorithm

Metric path planning algorithms share the same objectives and output and also internal representations. The algorithms take a volume of space and distill it to a more simple representation, called the *configuration space*, such as a Voronoi graph, a regular grid, a quadtree, or hybrid free space/vertex graph. Given the ubiquity of maps which use a grid-based coordinate structure, regular grids are the most common structure. The planning operation over the configuration space can be further divided into *graph* or *wavefront* planners.

Graph planners stem from the AI search community. They convert the grid into a connected graph and use a variant of the A* optimal graph search algorithm to find the optimal path between the start and goal location. The edges between the nodes of the graph represent distance. Obstacles are "missing nodes" from the graph. Each graph node on the path can be a waypoint, though in the early1990s some nodes were eliminated through path relaxation techniques to smooth the path and simplify localization demands on the perceptual system. With the ascendance of GPS for localization, path relaxation is now frequently skipped.

Wavefront planners originated from the graphics community. They also use the regular grid configuration space, but use graphics coloring algorithms instead. These can be thought of as a heat flow from the starting location spreading outward (coloring) to adjacent cells. When the "heat" reaches the goal location, the algorithm is complete and the shortest path can be easily determined through gradients.

Graph planners dominate unmanned ground vehicle path planning, possibly because of their use in the DARPA Autonomous Land Vehicle Project and exclusive use in follow on-projects (UGV by the Army Research Laboratory. The D* algorithm (Stentz, 1995), which is an A* optimal search repeated for all possible starting points to a goal is the de facto standard. This commitment to graph planners may have been premature and have negatively impacted the development of terrain-sensitive planners.

Terrain-sensitive Path Planning Overview

Terrain-sensitive path planning is a newly emerging area within the path planning community that incorporates the impact of the terrain on execution as well as the shortest distance. Historically, terrain has not been a criteria for optimality for several reasons. First, until the UGV Demo III project, there was no demand to go off-road. Since the UGV was restricted to roads or at the worst case, open fields, sophisticated terrain planning was not essential. Second, incorporating terrain into graph planner and maintaining optimality is very difficult. D* and A* planners require an admissible heuristic function to generate the optimal path with the minimum complexity. Euclidean distance is ideal because the distance from a node to the goal can be determined from the map. Admissible heuristic functions with two or more variables, in this case distance and traversability, are notoriously difficult to construct without sacrificing low order complexity. Third, terrain is related to the velocity, turning radius, and traversability of a particular vehicle configuration. But often this is a red herring stemming from indoor navigation, since path planning outdoors is at the 10M or larger resolution- far beyond the level to worry about turning radii and vehicle velocity. Fourth, terrain data is often uncertain. The level of resolution, process of map making, age of the maps, influence of seasons on maps. and the difficulty in accurately projecting changes in foliage create problems. Independently of the intrinsic challenges of incorporating terrain into path planning, most researchers have not had access to outdoor UGVs and so have not experienced the true demands of the field.

D* methods either ignore terrain until it becomes a problem during execution, *prune* unfavorable terrain and vehicle configurations from the graph (e.g., it is an obstacle) during preprocessing, use *time to goal* rather than distance to goal as the metric, or a combination of all three, see (Guo & Parker, 2002). Pruning eliminates valuable options: going through Area K may not be fast but at some point may be better than standing still. Using time to goal appears reasonable though coarse, and also side-steps the hard problem of how to convert the impact of terrain on a particular vehicle to traversibility speed.

Wavefront planners appear better suited for incorporating terrain effects. Instead of treating terrain as an obstacle, wavefront planners associate a density with the terrain. The heat flow through the area is slowed but not arbitrarily eliminated. However, as with graph planners, the impact of associating a terrain with an accurate density or transit time is still challenging. The best known is Trulla (Murphy, Hughes, Noll, & Marzilli, 1999), which was developed by the University of South Florida and adopted by the Naval Research Laboratory.

The key advantages of wavefront planners over graph planners are that they incorporate terrain in the regular grid (essentially, as a map overlay) rather than in edge weights that must be separately maintained and computed, and that all possible paths to all possible goals are pre-computed as a side effect of the wave propagation (or, free path planning that can be cached on a UGV). There are certainly alternatives to graph and wavefront planners such as the use of genetic algorithms (Farritor & Dubowsky, 1997) and case-based reasoning (Kruusmaa, 2003), but these are not widely accepted.

Path Planning for Teams of Robots

A related issue to path planning in UGVs is path planning for teams of mobile robots. Only a few approaches explicitly consider the impact of terrain on a team of robots and in each case, the impact of terrain is handled during execution: the path of the robots or lead robot is first computed and then during execution, the robots adapt. Approaches include considering the robots as connected by springs (Lawton, Beard, & Young, 2003), using a control graph (Desai, 2001), or Extended Kalman Filtering (EKF) to maintain the correct elevation profile as well as formation (Madhavan, Fregene, & Parker, 2004).

Terrain Interpretation for Path Execution and Learning

While terrain-sensitive path planning uses *a priori* terrain knowledge, the robot itself has to execute that path in an open world where expectations and plans may be invalidated. As a result, the robot needs to be able to sense the current terrain and adapt accordingly. Or in other words, terrain-sensitive path planning is a top-down process operating on symbolic data. A bottom-up learning process operating on perceptual data is needed to update maps and propagate successful navigation strategies. We refer to this as the "10m problem": how to connect the symbolic data that exists in maps with 10m x 10m or 30m x 30m resolution with the perceptual data that the robot collects.

There are four levels of adaptation defining how a robot would adapt to the terrain:

1. *Sensori-motor*, or behavioral, changes. Here the robot would keep using the active behaviors selected by the TAH-RI system, but would change their parameters. For example, if the terrain was "bumpy" and causing problems with sensor stabilization, the robot would slow down.
2. *Schematic*, or script-level, changes. In this case, the instantiated behaviors are no longer sufficient and so the robot must change the behaviors, not tweak the parameters. One

example is when the Cartographer creates an expectation, such as the estimated time to arrival, and that expectation is not being met. A subscript is instantiated which will then request diagnostics and eventually an update of the map and a new set of paths, allowing the robot to cope with problems. Another example is changes in environmental conditions, where the fall of night or rain interferes with a video camera and the system adapts by switching to a no-light illuminator.

3. *Deliberative* changes. This level of change begins to show the power of TAH-RI. As the robot adapts its behaviors and parameters to the terrain, it learns the association with this terrain type.
4. *Distributed* changes. Here the robot propagates what it has learned to other robots or works with other robots to divide up the computational task.

However, these four levels of adaptation presume the robot has the ability to detect terrain changes. As will be seen below, real-time terrain interpretation is an open question.

On-board Terrain Interpretation

A UGV has only two sources of information about the terrain at the 10m or less resolution: 1) from a forward deployed source with a limited look-ahead such as HUMINT, a small UAV (Miller, 2002; Stentz, Kelly, Herman, & Rander, 2002) or another UGV or 2) from its own onboard sensor suite. However, forward or projective interpretation can be viewed as onboard interpretation that is distributed to other agents. Therefore, the body of literature in real-time terrain interpretation has focused on onboard interpretation. Onboard interpretation approaches can be divided into two categories: proprioceptive and exteroceptive.

Proprioceptive Terrain Interpretation

Proprioceptive terrain interpretation uses internal sensors such as vibration, wheel torque, and position to determine terrain. (Howard, Seraji, & Tunstel 2001; Larson, Voyles, & Demir 2004) use inclinometers to determine the slope of the terrain. (Larson, Voyles, & Demir 2004) go further and include a measure of the "gait bounce" extracted from the video camera; essentially the more the camera has to compensate for visual servoing errors, the rougher the terrain. (Iagnemma and Dubowsky, 2002) use both vision and audition to detect gait bounce and wheel-ground interaction.

The advantage of proprioception is that it is "built in" the robot and allows the robot to adapt its speed to the terrain. The disadvantages are numerous. These methods are generally limited to surface properties and do not detect foliage changes. There is no classification per se, but rather these methods capture a stimulus-response relationship between vehicle speed and the salient terrain property. It is also not particularly useful for detecting changes in symbolic expectations (e.g., "why is there an obstacle blocking the road?").

Exteroceptive Terrain Interpretation

Exteroceptive sensors perceive attributes of the environment external to the robot. There are three main categories of exteroceptive sensors used for terrain interpretation on robots: multispectral imaging, ladar, and color video. None of these sensors, individually or combined, have provided a reliable solution to terrain interpretation. This suggests that for the short term, systems such as TAH-RI which allow multiple levels of cues ("something's wrong here but I don't know what") and also the involvement of the human in the diagnosis process will be critical for the successful deployment of UGVs.

Multispectral imagers have been used on large truck sized robots and have produced good classification results, see (Bhanu, Symosek & Das, 1997). However, these sensors are very large and unlikely to be miniaturized enough to fit on small UGVs within the next 5 years.

Ladar is a much smaller sensor and has become increasingly popular. It is a staple of the Army's Demo III XUV program (Albus et al, 2002). (Castano and Matthies, 2002) used ladar to detect dense foliage and trees, but had problems with "thin" trees. (Hebert, Vandapel, Keller, & Donamukkala, 2004) produced algorithms for generating 3D models of the environment, including obstacles, in real-time. However, foliage remained a problem. (Ollis & Jochem, 2003) also used ladar for obstacle avoidance and rudimentary terrain analysis. In general, ladar appears useful for obstacle avoidance and promising for some types of foliage detection. It will require a great deal of work to establish the correct classes of perceivable terrain as well as deal with obstacles partially hidden by foliage (the rock behind the grass).

Color video is the most popular sensor for extracting terrain information, possibly because color video cameras are small and every robot has one. There is certainly the existence proof that humans can discern terrain visually. Many different methods have been tried and none appear successful (Davis, 1995; Lin, Hays, Wu, Kwatra, & Liu, 2004; Dima, Vandapel, & Hebert, 2003). Some improvements were made when color video was used in conjunction with ladar, see (Talukder, 2002).

Findings Regarding Terrain-Sensitive Path Planning & Interpretation

To summarize, graph planners, especially D*, dominate path planning, but wavefront planners appear to have significant advantages for terrain-sensitive path planning. The biggest problems with current approaches stem not from the algorithms themselves, but rather from the integration of path planning into the large navigational enterprise. Upstream of the path planner in the navigation process is the map input. Path planners require a priori maps, yet these maps can be wrong and the terrain data is uncertain. In general there is no adequate catalog of terrain vs. platform traversability characteristics; all such systems use ad hoc metrics. Downstream of path planning is execution. A path planner can be optimal and correct, yet a UGV in the field may not be able to execute the path due to GPS area denial or unexpected terrain. In practice, there is often no way for the robot to use its path planning assumptions with its current perception to detect expectation violations. Finally, the "10M problem" is the most pervasive. Outdoor path planning is at a relatively coarse, on a 10m grid. Within this 10 meter squared area, numerous obstacles, variations in terrains, and other navigational issues can arise that cannot be captured in advance by path planning.

The state of the art in a robot determining terrain is minimal for navigation and not supportive of higher-level reasoning. This suggests that attention must be paid to the perceptual abilities of the robots and how software and humans can interact with the limited data to produce robust results. One observation is that there is no standard test bed or data set for terrain by which to compare terrain interpretation algorithms.

Task 2 Results: Determine What Tool Design Changes Needed.

In Task 2, our team determined necessary tool additions and modifications based on the results of Task 1 for fielded command and control systems like the Army's FBCB2 and the USMC's C2PC, and OTB-SAF simulation system used for training and SMART investigations of potential systems and new operational concepts in the various BattleLabs. During Phase I

several team members were given the opportunity to see FBCB2 in action, and to get more insight into its underlying infrastructure from that systems' developers at Northrop-Grumman's Orlando office. We have reviewed the FBCB2 manual online, and reviewed our corporate experience with both C2PC and OTB-SAF.

Common Terrain Features and Combinations of Other Terrain Analysis Results

New functionality will need to be added to the Terrain_V5 code base. This new functionality will include terrain feature (e.g., hill and ridgeline) determination and union/intersection of geometrically defined objects. All existing Terrain_V5/6 module terrain calculations are affected by different factors including vehicle type and echelon size. There is currently functionality to query for features specific to a particular unit. We have built an architecture that allows us to search for specific characteristics within an area and overlay or combine with other queries if desired, although this capability should be expanded and refined. For example, we can query an area for only major roads that do not go through a city. The basic operations use the =, <, <= , >, >= operators for searching. They produce values that can be combined using 'and', 'or', and 'not'. This gives us a logical design in querying terrain databases giving us a very flexible design for meeting future requirements with lower costs for expansions and possibly slightly lower costs for refinements of these capabilities. A key modification of great interest would be the ability to modify and write back to VPF as updated information about actual features and characteristics represented as *f-codes* would be quite useful, both for individual robots/humans/units and for sharing this info with other friendlies also needing to traverse or otherwise reason about a given area. This will be a very large task and may be beyond the scope of TAH-RI Phase II without scoping it down carefully. It would also be helpful to be able to use older data formats, like DFAD, which will take some effort to develop.

Currently, the TERRAIN_V5/6 module used in C2PC for the USMC has functionality to cache vectorized road data for the use of finding road junctions. In the future, it should use the road vectors plus the junctions to create a shortest path graph for all road junctions in the area taking into consideration the goodness of different roads (although this again gets into the area of goodness for what particular purpose). Currently when the module wants to get information about any area (e.g., Boxy or Irregular), it has to query and grab data for a rectangular area. Due to the fact that it rasterizes such data, over a large area a raster eats up a lot of memory regardless of whether or not the system actually needs all that information. Thus, to handle irregular objects which are essential to working with real-world missions and commander's intent information, we would like to develop two main algorithms:

- Given two or more polygons, take their union or intersection to create a new polygon.
- Given a polygon, extract VPF and DTED data only for the regions inside the polygon.

To do this we must be able to directly access the VPF data.

Note also that ensuring CJMTK compliance, where appropriate, in any additions or changes in structure or function of existing tools should also be kept up.

Examples of Trulla Terrain-Sensitive Planning On-Board Robot

In order to illustrate the utility of the Trulla path planning algorithm as part of the TAH-RI system and how it fits within the architecture, Trulla was implemented on a RWI ATRV-JR mobile robot and three demonstrations were conducted in a field with terrain diversity and urban

structures. The first two demonstrations show the nominal terrain-sensitive path planning function and the third shows the replanning in response to a threat.

In each scenario, the Trulla algorithm runs on the robot's Operator Control Unit (OCU), which is a Gateway laptop. It computes the set of waypoints, then transmits the list to the robot. The robot now has a complete plan and reactively executes navigation between waypoints. Note that the Trulla algorithm could reside directly onboard the robot or on another distributed control workstation.

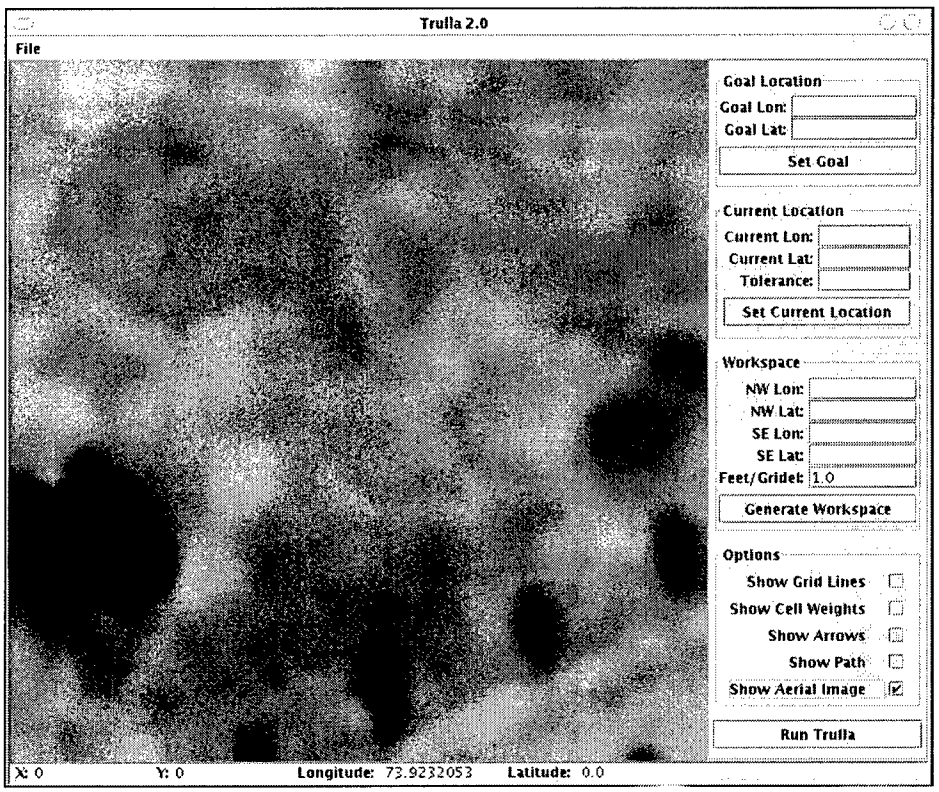


Figure 5. Satellite image of the robot test field.

Example Test Area Terrain

Figure 5 shows a satellite image of the robot test field. The darkest areas are trees. There is an oak tree in the lower left. A row of four palm trees line a sidewalk extending from the lower middle to the lower right of the image. A stand of palmetto bushes is above the rightmost palm tree. A road is below the sidewalk, though not clearly visible. The field itself had some terrain diversity, with grass and an area with sand.

Scenario 1 and 2: Paths Around and Through Unfavorable Terrain

In both scenarios, the robot was given starting and goal locations. Based on the shortest distance and the traversibility and navigation constraints, Trulla computed an optimal path which the robot executed. The first two scenarios also used the same terrain weighting, shown in Figure 6, as increasing shades of blue. The trees and shrubs were marked as obstacles (highest value of unfavorable). The sand pit was marked as mildly unfavorable. In addition, the sidewalk

was marked as highly unfavorable not because of mobility concerns but due to constraints generated by TAH-RI.

Figure 7 shows the output of Trulla. The start location is in green and the goal is in red. The white is the optimal path with GPS waypoints. The arrows show the result of the all-paths computation- if the robot deviates from the path, these "arrows" describe the alternative optimal path from the new location. In this case, Trulla routes the robot around the sand pile, since the robot can make better time on grass than on uneven sand. Figure 8 shows robot on this path.

In Scenario 2, the start and goal locations were chosen so that tradeoff between avoiding less favorable terrain and moving to the goal rapidly was less. As shown in Figure 9, Trulla directs the robot to take a shortcut through the sand pile. Figure 10 show the robot navigating using GPS through the sand pit.

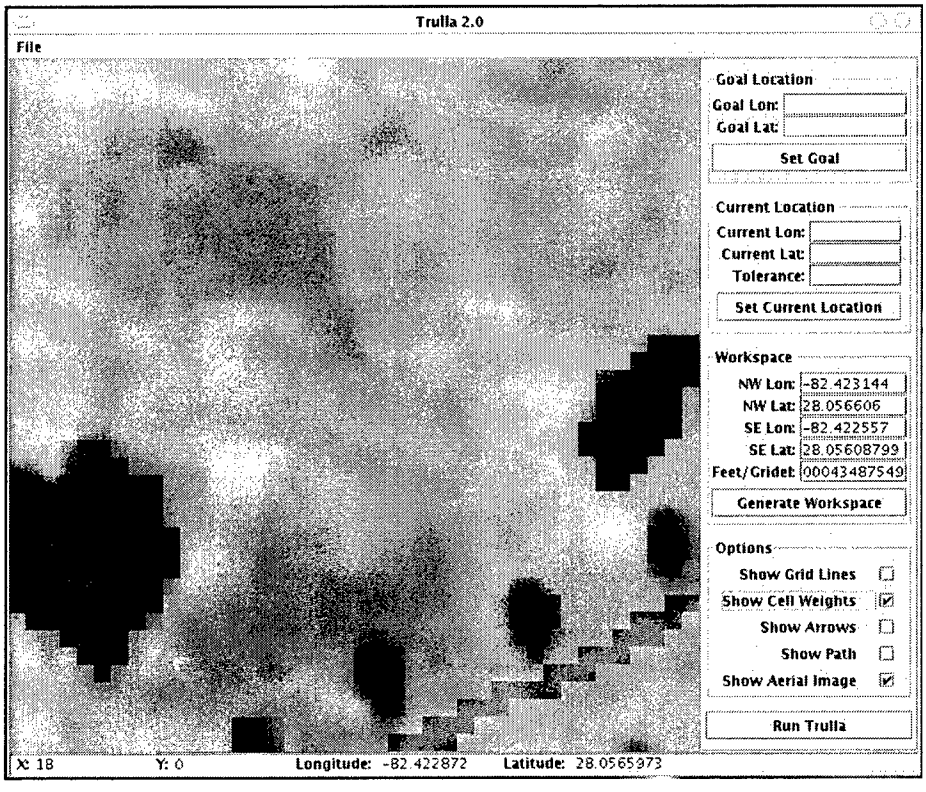


Figure 6. Overlay of terrain weighting on satellite image.

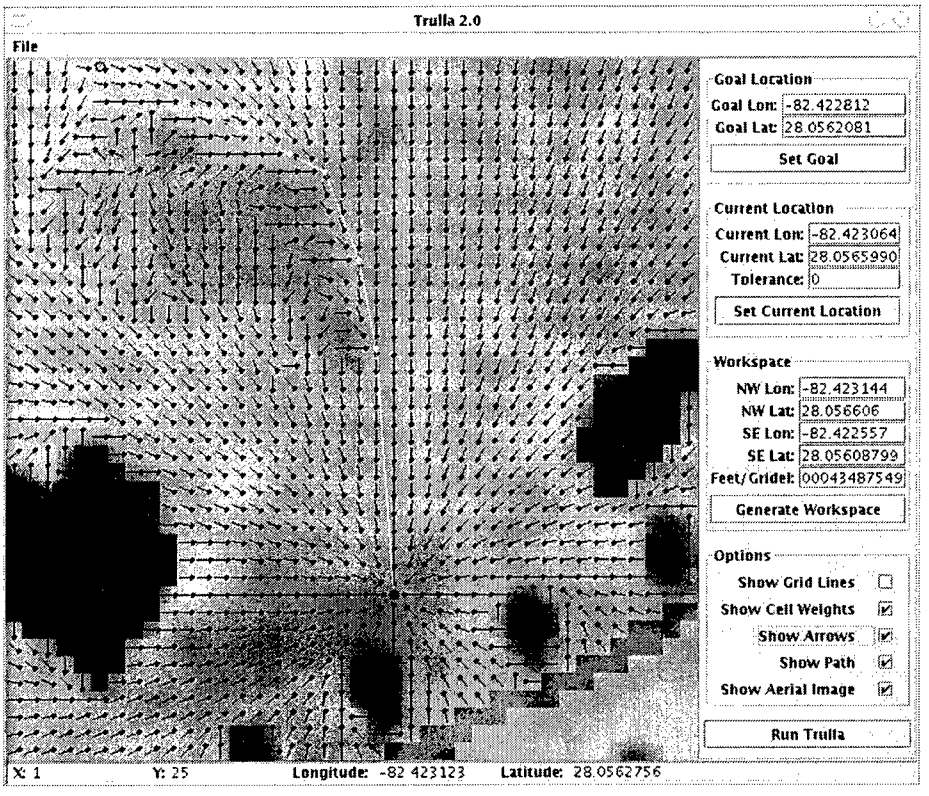


Figure 7. Satellite image overlaid with Trulla path and alternative paths.

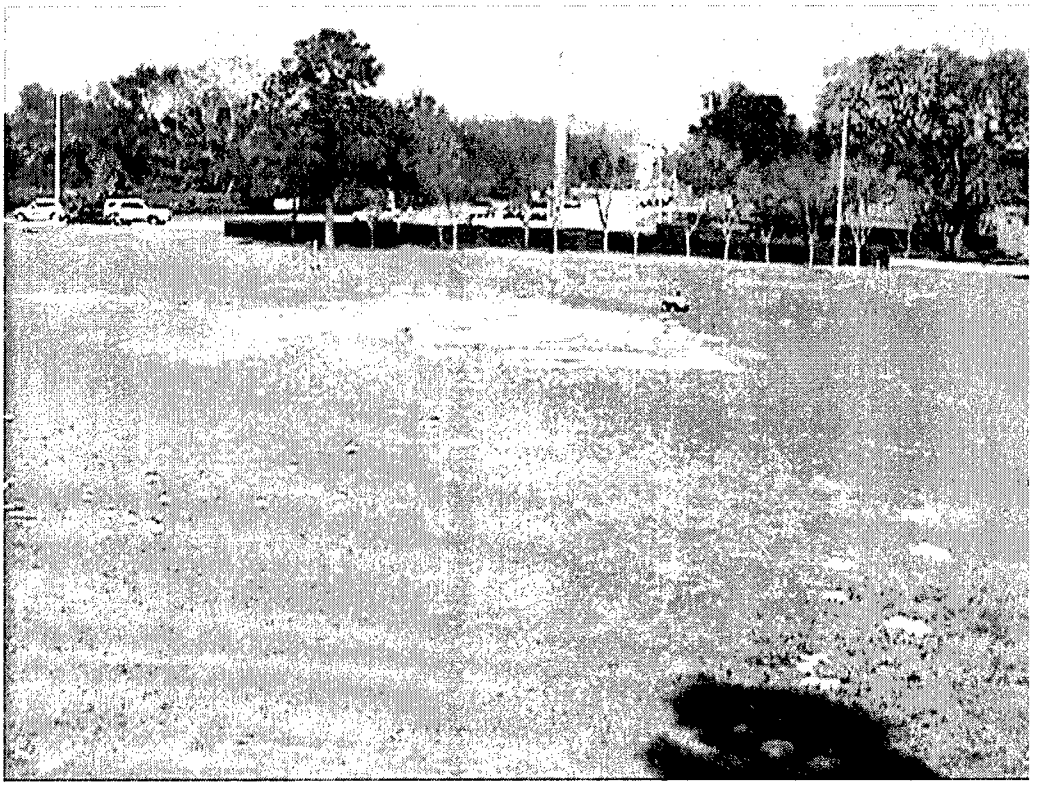


Figure 8. Robot navigating around sand pit in scenario 1.

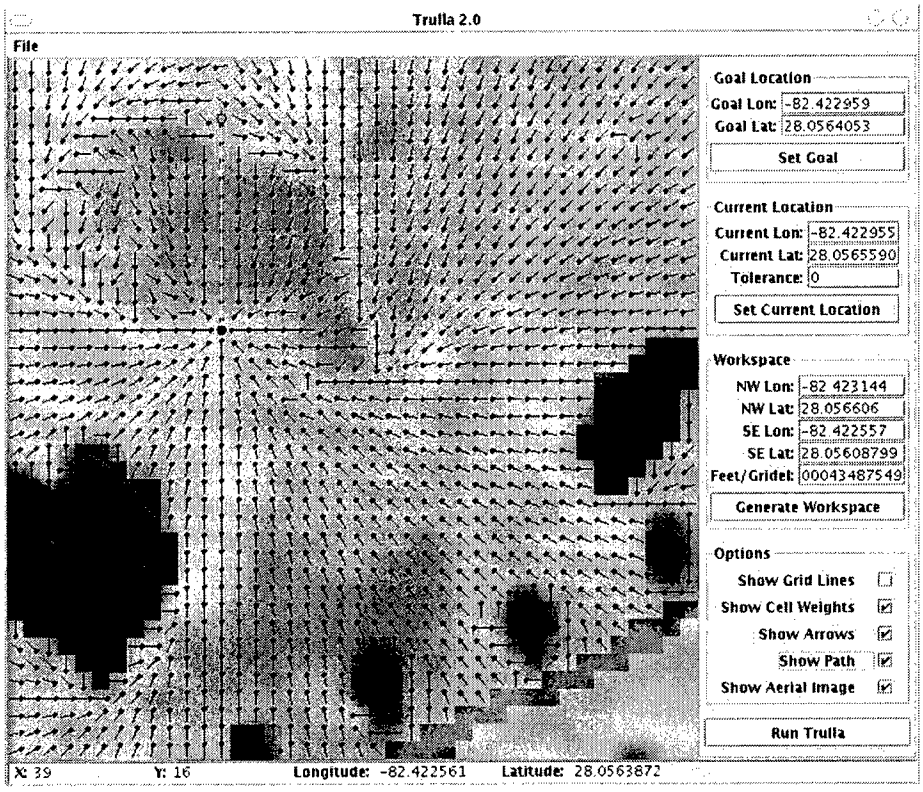


Figure 9. Satellite image overlaid with path and alternatives for Scenario 2.

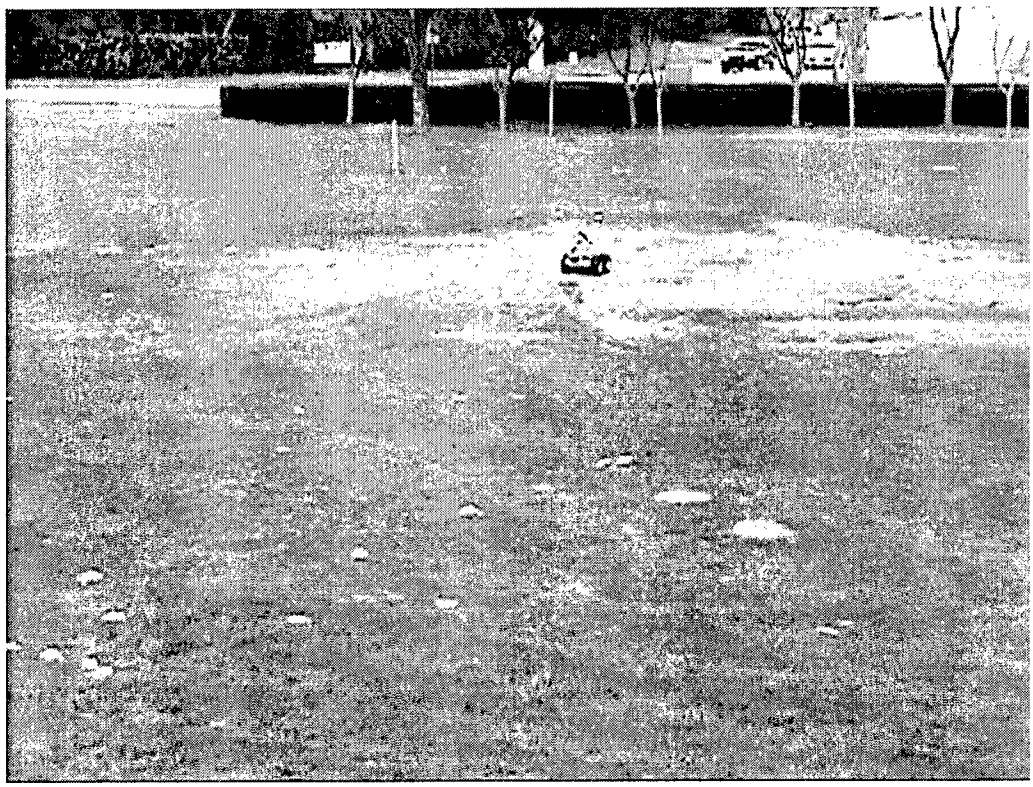


Figure 10. Robot following path through sand pit.

Scenario 3: Replanning in Response to Threat

Scenarios 1 and 2 essentially duplicate results from previously published work, while Scenario 3 shows new results in using Trulla as a part of the cognitive system. In this scenario, the TAH-RI system is informed of a threat, possibly an unmanned aerial vehicle acting as a sentry as in Figure 11. The TAH-RI system immediately reasons about the threat, changes the map to incorporate new constraints, and generates a new goal.

In Figure 12, it can be seen that the terrain interpretation is now radically different. Open areas are now marked as unfavorable. Reasoning about the tree coverage and visibility of the UGV from the helicopter produce a new understanding of the environment (that the only place to hide is under the oak tree) and forms a new goal. This leads to the new path(s) in Figure 13 and the robot flees (Figure 14) to the cover of the nearest tree.

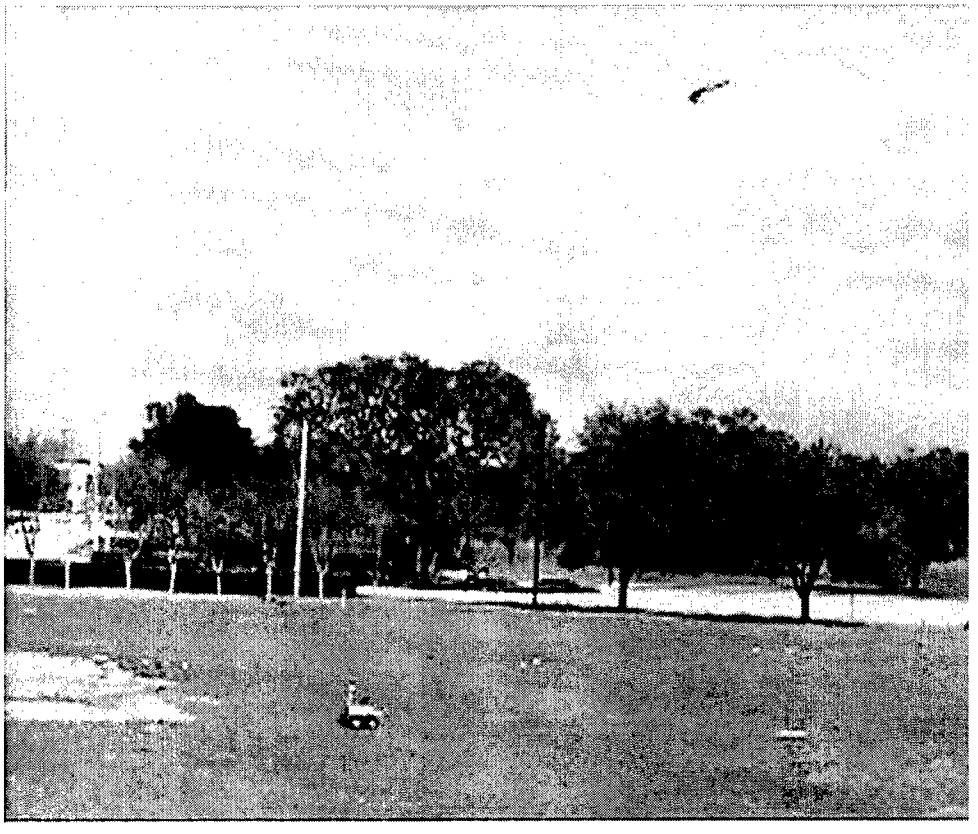


Figure 11. Unmanned aerial vehicle conducting a search to detect intruders.

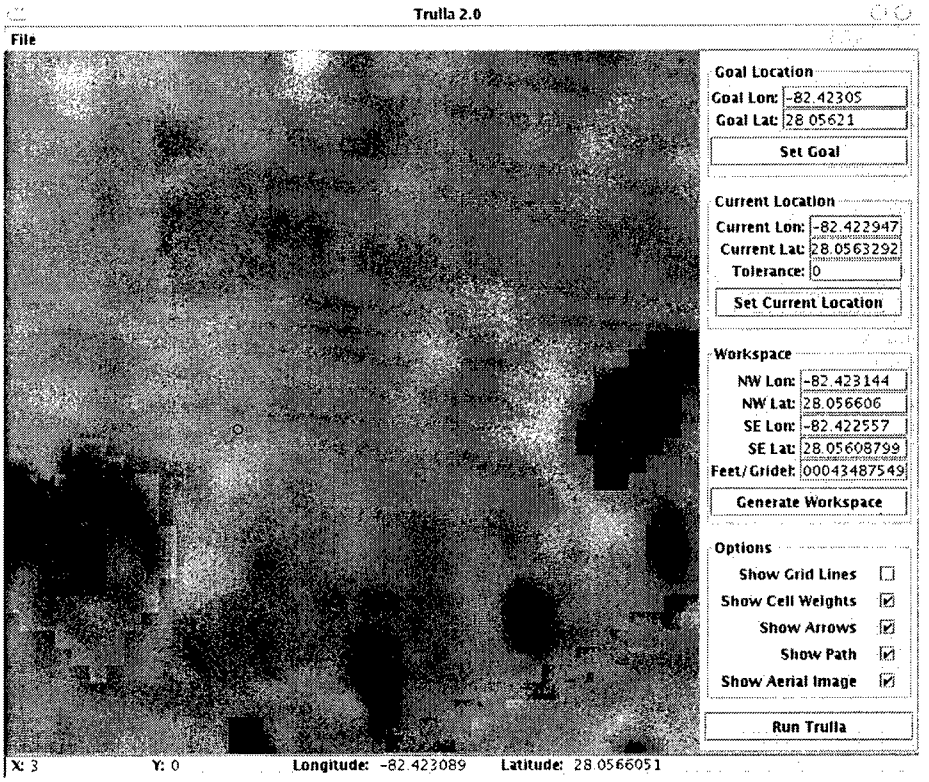


Figure 12. Different terrain interpretation due to threat.

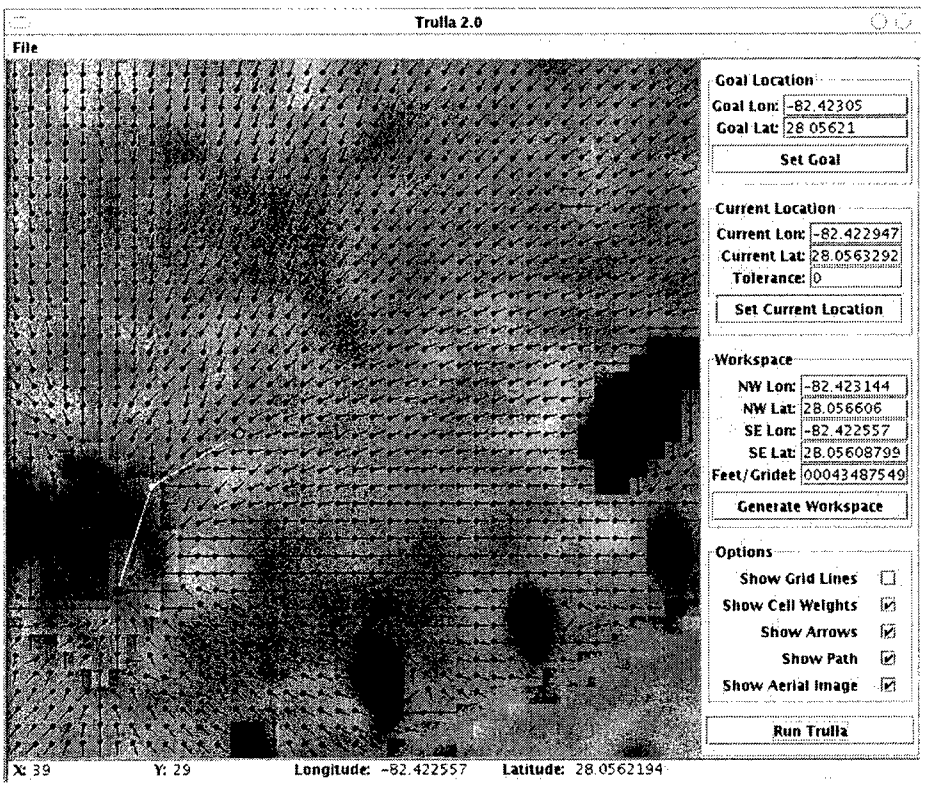


Figure 13. Resultant goal and path in response to threat.

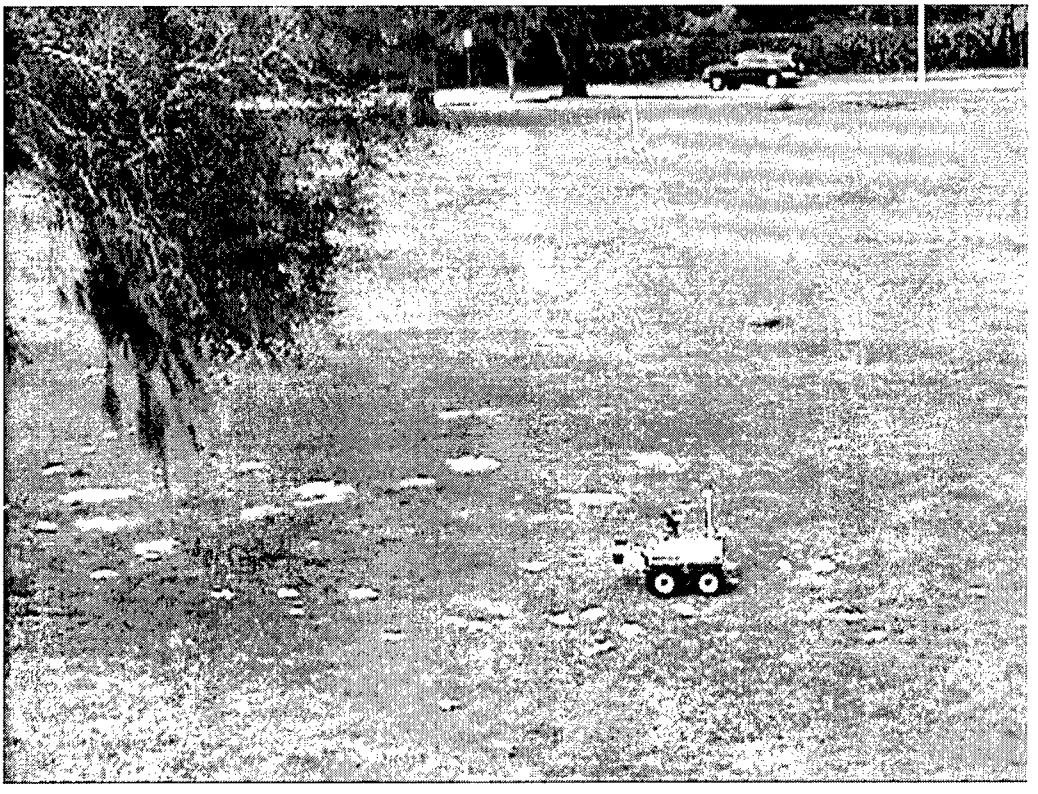


Figure 14. Robot being directed to hiding under a tree by Trulla in response to the threat.

Discussion of Examples of Terrain-Sensitive Planning

These demonstrations show that Trulla is a workable terrain-sensitive planner. It uses a map representation that readily supports reasoning and propagation of constraints. It also supports distributed computing with Trulla being able to reside on the robot or a network node. The algorithm does not need to continuously recompute the path based on the robot's actual location in order to be optimal during execution since it computes the best path from all possible locations as a side effect. It can recompute paths in real-time given new constraints or situations. Coupled with GPS localization, robots can avoid unfavorable terrain that they cannot themselves interpret in real-time. Figure 8 shows the robot navigating around the sand pit without having to sense it. Given the problems with onboard terrain interpretation, this feature is an advantage.

The demonstrations did not show some additional key features of Trulla that will be demonstrated in Phase II. First, Trulla provides the robot with all possible paths, not just the waypoints. If an unmodeled obstacle introduces a path deviation, the deviation may actually be favorable and lead to a short cut. Rather than have the robot go to the original waypoint, Trulla will direct the robot to the most optimal path without replanning. Second, Trulla uses the dot product of the current path with the planned path to detect when the robot had wandered off course, most likely due to a series of unmodelled obstacles or an error in the map, and request map updating and replanning. This feature was not implemented in Phase I.

Task 3 Results: Investigate Use of Commander's Mission Intent.

CHI Systems has significant experience with this problem and with a variety of partial solutions that have been attempted in the past. Truly solving this problem requires a mixture of old and new approaches, and it is quite possible that the state of the art in key technical areas

(e.g., intelligent software) may not yet be far enough advanced to make a full solution possible. What makes commander's intent such an interesting problem is that current oral or written statements of commander's intent seem to often focus primarily on providing additional insight into the commander's values as applied to commander's assessment of range of anticipated potential situations and how they are expected to unfold, other possible ways in which they might alternatively unfold, and guidance as to the commander's intentions about how his forces are to position themselves to execute that commander's plan as envisioned while ensuring that anticipated alternative ways the battle situation might unfold are covered using commander's values, situated beliefs, judgments, and tactical decisions. In large part, a key value of commander's intent seems to be the communication to subordinates of an elaboration of how the mission and associated plan and alternative plans and pre-planned responses are based on the commander's beliefs, values, judgment, and expectations as each are applied to the range of anticipated possible situations that might occur.

Interestingly, advances over the past few years in intelligent agent's abilities to provide humans with explanations of agent's actions, plans, and the reasoning underlying them may be closely approximating commander's intent statements. How close a match they are is, unfortunately, still an open question. In some of the authors' opinions, the match is quite close. To many AI researchers and cognitive scientists and engineers studying that problem, what their agents' have to do to generate explanations seems to be well-covered in the above description of an intent statement covering a commander's situated beliefs about the current and anticipated situations, and how the commander's values are to be applied to battlefield decision making under the current and anticipated situations by subordinates, as well as how these commander's intent statements further elaborate how planned strategies, operations, and tactics are to be applied and executed as the situation unfolds.

Commander's intent must be captured from human commanders in a way in which both robots and human subordinates understand it, and can reason about alternative solutions when faced with, in the example of path planning, an unforeseen obstacle or threat. General HRI issues underlying successful communication of the commander's intent are addressed in the discussion section, but details of GUI design criteria to be applied in prototyping and then building a GUI to accomplish this challenging task are described below.

Current digital C2 tools (and especially simulation systems like OTB) provide little or no support (other than some form of instant messaging "solution") for enabling a commander to elucidate his beliefs about which of the many possible enemy alternative courses of action (COAs) he judges to be worthy of including in contingency planning, and the details of how he wants to handle such contingencies if they arise. Also missing are means of capturing key guidance about value judgments and how they should apply to envisioned contingencies and unanticipated situations or evolutions of situations. However, when it comes to capturing how the enemy will most likely behave, and planning own forces operations, current digital tools do provide useful means of at least creating and sharing representations of the various COAs (real or imagined) through graphical overlays of maneuver graphics and similar representations. Additionally, means of capturing, storing, and sharing details of the synchronization matrix for current planned (and alternative) COAs is possible on at least some of these tools or near-future prototypes. Thus, it may be possible to provide full GUI support for capturing commander's intent by augmenting such representations with elucidation of value judgments, relative merits and special dangers posed by each alternative, the commander's preferred tactics, techniques, and procedures (TTP), and how they all apply to various envisioned situations and plans. Due to

the vital importance of commander's intent for enabling autonomy, more work is needed to prototype and test means of advancing the state of the art in this area.

Task 4 Results: Assess How to Integrate CROP with Robots.

Our team has completed our investigation of this issue and the related issue of which details and which analyses need to be done on-board an autonomous robotic system vs. off-board through use of disembodied intelligent software agents as surrogates for their embodied cousins but with access to significantly more computational power to aid in integrating these analyses results and data sources. The results of our assessment have been folded into refinements of our initial design concept for the underlying TAH-RI sub-assembly architecture addressed in Task 7, below.

A Multi-Resolution Relative Location Grid (Multi-Grid) Spatial Representation

To effectively reason about METT-T factors, battlespace-aware robots need means of integrating CROP with terrain understanding to enable both better navigation and mission performance. Effective implementation of such a capability will require that a number of technical obstacles be overcome. Issues which have currently been identified exist in the areas of methods of data aggregation, storage, entity notification and efficient methods of recalculation.

Path planning and decision making using TAH-RI will require that data from a number of sources be aggregated and stored. Data sources that are expected to be used include terrain analysis results, direct fire information for known weapon systems, indirect fire information for known weapon systems and known unit position and associated unit parametric data. These data can be further broken down into four broad areas of focus: personal, group personal, non-associated individual and non-associated group. Appropriate aggregation of disparate data types will be based on results of analyses of established military practice and Soldier expertise.

For purposes of data retrieval and analysis, aggregated data will be used within TAH-RI decision-making components in a multi-resolution grid format. This data format involves increased data granularity as distance from focus (e.g., "my current location") is increased, as shown in Figure 15. Figure 16 illustrates how size of minimum grid element (i.e., scale of Multi-Grid) affects coverage and resolution of Multi-Grid spatial representation and query tool.

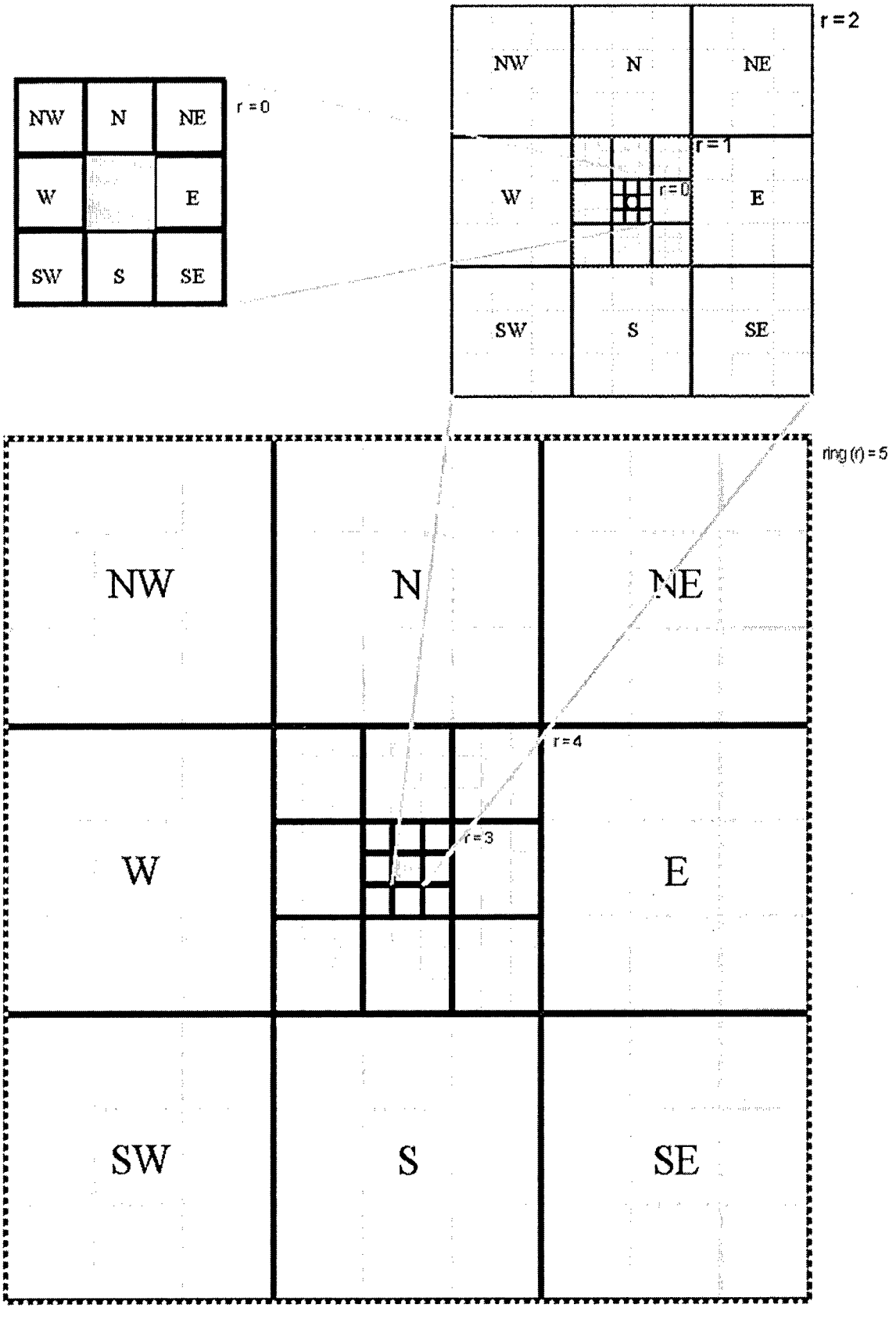


Figure 15. Multi-Resolution Relative Location Grid (Multi-Grid) Spatial Representation

scale =	10	meters								
Ring No.	0	1	2	3	4	5	6	7	8	9
Distance Added	10	30	90	270	810	2,430	7,290	21,870	65,610	196,830
Range (m)	10	40	130	400	1,210	3,640	10,930	32,800	98,410	295,240
Number of Cells	9	81	729	6,561	59,049	531,441	4,782,969	43,046,721	387,420,489	3,486,784,401
Multi-Layer Cells	9	17	25	33	41	49	57	65	73	81

scale =	30	meters								
Ring No.	0	1	2	3	4	5	6	7	8	9
Distance Added	30	90	270	810	2,430	7,290	21,870	65,610	196,830	590,490
Range (m)	30	120	390	1,200	3,630	10,920	32,790	98,400	295,230	885,720
Number of Cells	9	81	729	6,561	59,049	531,441	4,782,969	43,046,721	387,420,489	3,486,784,401
Multi-Layer Cells	9	17	25	33	41	49	57	65	73	81

scale =	100	meters								
Ring No.	0	1	2	3	4	5	6	7	8	9
Distance Added	100	300	900	2,700	8,100	24,300	72,900	218,700	656,100	1,968,300
Range (m)	100	400	1,300	4,000	12,100	36,400	109,300	328,000	984,100	2,952,400
Number of Cells	9	81	729	6,561	59,049	531,441	4,782,969	43,046,721	387,420,489	3,486,784,401
Multi-Layer Cells	9	17	25	33	41	49	57	65	73	81

scale =	1	kilometers								
Ring No.	0	1	2	3	4	5	6	7	8	9
Dist. Added (km)	1	3	9	27	81	243	729	2,187	6,561	19,683
Range (km)	1	4	13	40	121	364	1,093	3,280	9,841	29,524
Number of Cells	9	81	729	6,561	59,049	531,441	4,782,969	43,046,721	387,420,489	3,486,784,401
Multi-Layer Cells	9	17	25	33	41	49	57	65	73	81

scale =	10	kilometers								
Ring No.	0	1	2	3	4	5	6	7	8	9
Dist. Added (km)	10	30	90	270	810	2,430	7,290	21,870	65,610	196,830
Range (km)	10	40	130	400	1,210	3,640	10,930	32,800	98,410	295,240
Number of Cells	9	81	729	6,561	59,049	531,441	4,782,969	43,046,721	387,420,489	3,486,784,401
Multi-Layer Cells	9	17	25	33	41	49	57	65	73	81

Figure 16. Example Multi-Grid Coverage Areas at Five Different Scales

An efficient local addressing scheme for data stored in this format must be developed. Furthermore this addressing scheme must allow for efficient conversion to a global addressing scheme for effective data caching. An outline of a reasonable local addressing scheme follows:

[ring : ring element : sub-element]

Where ring is the number of rings desired element falls from the center, ring element addresses one of the eight grid squares in the ring (e.g. E is 0, SE is 1, S is 3, etc.), and sub-element address refers to one of the nine sub-elements of the selected grid square. Using this addressing method will allow for easy description of areas of tactical interest. It will also be necessary to develop routines to convert a C3Core World_Point to an address in the local system

and to convert local addresses to a global addressing scheme. Conversion of World_Point to local addressing should be fairly easy to accomplish. Conversion in the other direction, from Local to Global addressing will require a little more work as the number of different possible offsets increase exponentially with the ring aggregation level.

Importantly, note that the rectilinear grid system depicted above could, in a more advanced form, could be composed of more meaningful "concentric areas" that have specific tactical meanings. For instance, ring 0 could be defined as having its center at a robot's current location and an outer boundary based on how far that particular type of robot might be expected to move in some specific period of time (e.g., 5 minutes). Note that as terrain impact on mobility is factored into this calculation, this outer boundary becomes deformed into an irregular polygon surrounding the robot's current position. Moving uphill on a scree (i.e., loose rocks) slope will force the intrepid robot to travel much more slowly (if at all) than on relatively flat solid ground with no impediments. More interestingly, one could define another ring further out from an armed robot's current location with an outer boundary as the robot's own internal sensors' maximum range under current conditions (constrained by observability impact of terrain), and an inner boundary as the robot's on-board direct fire weapons' maximum range in each direction under current conditions (constrained by the terrain limitations on fields of fire.). Each time the robot would access and assess the tactical situation for navigation and mission performance purposes, the particular shape and size of this "ring" would be freshly calculated and used to help interpret and make decisions about the tactical situation based on current CROP data. TAH-RI could, theoretically, be used in such a mode aboard a larger advanced robotic vehicle, although the computational constraints involved in recalculating this kind of dynamic spatial representation would likely be prohibitive.

In addition to an appropriate addressing scheme, it will also be necessary to provide for a two-tiered event notification system. Specifically, it will be necessary to have entities notified when other entities of interest come within a set distance of them. This notification will then alert the entity that it will want more detailed notification of the unit of interest's movements until the point at which that unit moves out of range again. More detailed notification will consist of notification whenever the unit of interest crosses a cell boundary.

In order to accommodate data presented in this format, frequent data aggregations will be necessary. A shift of one minimum size cell realigns the boundaries of all larger sizes of cells. In order to mitigate the time cost of recalculating on every boundary crossing a number of strategies may be adopted. Caching of previously calculated data would ease computation in the event of backtracking. Incremental subtractions and additions to larger cells would ease some computation as well. If this method is chosen, care will have to be taken so that errors don't creep in over time. Errors of this sort may be avoided by requiring a complete refresh after a certain number of moves. If large periods of inactivity are expected, cell values of moves within a given limit may be pre-calculated.

Task 5 Results : Determine What Mixed-Initiative Communications are Required.

A literature search has been completed, cataloging relevant mixed-initiative communications issues and approaches applicable to the issues addressed in this task. Requirements analysis based on the results of that literature search were completed, and their impact on GUI design and on overall TAH-RI architecture has been incorporated into the TAH-RI architecture results (Task 7) and the Human-Robot Interaction (HRI) discussions.

Mixed initiative architectures are needed to support flexible human-robot teams capable of responding to the changing interaction requirements related to accomplishing tasks in challenging environmental conditions (Adams, Rani, & Sarkar, 2004; Bruemer, Marble, Dudenhoeffer, Anderson, & McKay, 2002). Mixed initiative systems can support a variety of control levels, the implication being that both humans and robots will need an understanding of the conditions under which humans and robots gain and relinquish control, and how that transition is executed during terrain analysis tasks, this will be described further under 'Human-Robot Interaction with TAH-RI' in the Discussion section.

Task 6 Results : Assess Requirements for Real-Time User-Updatable Database(s).

In this task, CHI Systems drew upon our experience with the C2PC system and with our own C3DB software component, which is expected to form the basis for the TAH-RI real-time user-updatable database of terrain information and analysis results, as well as for being the means of communicating the CROP to individual humans and robots. Given the requirements and implications of design decisions made in other tasks, it appears that this anticipated approach will, indeed, provide the most capable approach available for solving this part of the terrain understanding problem. This assessment also affected our Multi-Grid design reported above in Task 6 results.

Task 7: Complete the TAH-RI Architecture.

TAH-RI architecture design is at the core of Phase I design and feasibility assessment. As a first step, based in part on the literature review from Task 1, our USF colleagues have completed encapsulation of the TRULLA terrain-based wavefront planner as a separate module and have integrated it onboard the ATRVjr robot designated for this Phase I effort, as described above. Initial Phase I design for integration of TAH-RI components using CHI Systems' C3 Architecture Framework (C3AF) was also completed in this task. Determination of how C3AF and the C3Core component technologies based on it, the iGEN® cognition engine, and the Distributed Field Robot Architecture (DFRA) should be further integrated in Phase II was a key activity in Phase I, including integration of the important results emerging from our joint work on Task 4. Descriptions of key enabling technologies to be used in Phase II implementation of TAH-RI and their relationships with the other results discussed in this report are provided below.

C3Core Component Technology

A key enabler for creating a viable TAH-RI sub-assembly is C3Core, CHI Systems' COTS command and control software component technology. C3Core is an object oriented, service-based software suite that allows developers to pick and choose a variety of command, control and battlefield visualization functions for reuse. Design tenets underlying C3Core software include:

- Core Sets of Reusable Services. Components of C3Core can be updated, redefined, and easily specialized to create software which can operate within a variety of platforms and domains.
- Platform, Operating System, and Technology Independence. A goal in the development of C3Core is to maintain platform, operating system and technology

independence. Currently ,the C3core operates natively under Microsoft's Win95/98/NT, Solaris 2.4 and 2.5x, Silicon Graphics Irix 6.x and Linux. An application written utilizing some of the C4I component ware provides a default interface if required, and can also run without a GUI as an embedded decision aid with a third party interface such as a Crusader howitzer or M1 Tank.

- No Assumption on Who Uses Services. The third property of the C4I component ware is that very few assumptions are made regarding to whom services will be provided, or how services will be provided. This requires that the internal system depend upon only abstract service interfaces and not on a specific implementation. This does not say that all Service Groups or components are completely independent of one another; there exists a conceptual abstract dependency within the services. For example, a graphics package needs to have a context from which to draw; this is a dependency which "makes sense." The graphics package does not care however if the context is a printed page, 3D display or an analysis package.

Figure 17 gives an overview of where the C3Core component technology has been applied in BattleLab experiments and demonstration of future technologies at Echelons Brigade and Below.

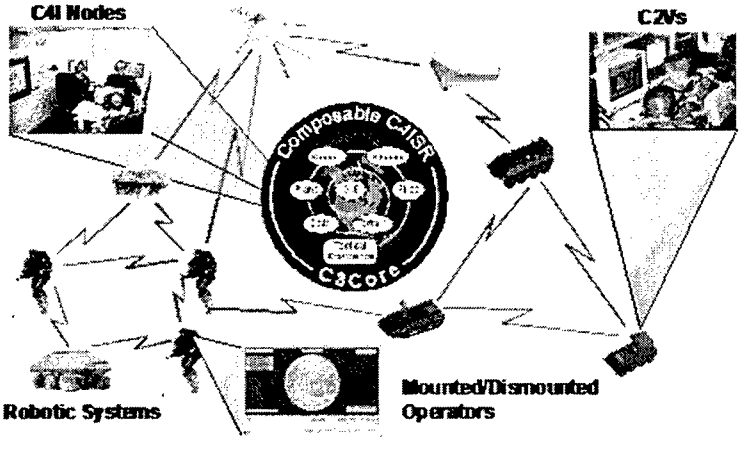


Figure 17. Variety of Scalable Composable Application Environments for C3Core Components

C3Core was used in the development of the Combat Decision Aiding System (CDAS) technology demonstration testbed. CDAS Objective Force Warrior (OFW) is described below as it provides one example of an existing digital C2 system that could be enhanced using TAH-RI, while also illustrating development using CHI Systems' existing C3 Architecture Framework (C3AF) core and the C3Core reusable software components built atop that core.

Example Application of C3Core Component Technology for C2 System

CDAS OFW provides multi-echelon netted fires capability, from one individual OFW equipped dismounted Soldier up to a whole Unit of Action Effects Control Center (see Figure 18 for the "combat view" CDAS interface). CDAS OFW facilitates:

- Collaborative Planning,
- Logistics Monitoring and Asset Visibility,

- Terrain Analysis for Sensor Placement,
- Issuing Digital Orders,
- Use of Robotic Vehicles,
- Text Messaging (Instant Messenger), and
- Situational Awareness Monitoring.

An experiment/demonstration was conducted at Fort Benning, GA, examining whether the individual OFW Soldier, fire team leader, and squad leader could reach back quickly to obtain support from Non-Line-of-Sight (NLOS) and Beyond-Line-of-Sight (BLOS) weapon systems, whether leaders could perform distributed interactive fires management of squad-level weapon systems, and the effects that could be expected from improving situational awareness for the dismounted leader and Soldier.

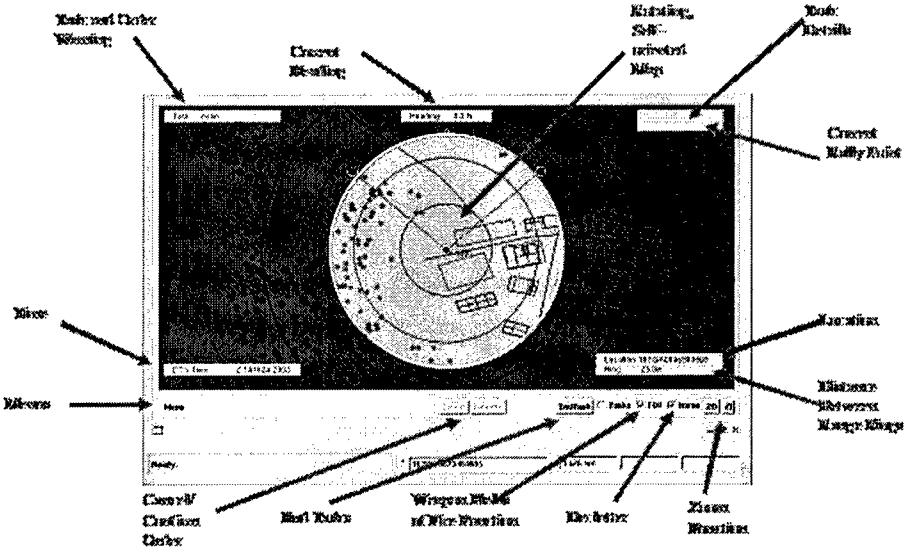


Figure 18. CDAS Combat View Interface

Several findings were reported from the experiment/demonstration. Overall, the results were successful, illustrating that a decision support tool can improve performance of a dismounted Soldier in the field. A few examples of the results are:

- Each of the Soldiers who participated in the experiment was able to call for fire using the OFW CDAS. By a large majority, the participants agreed that sending the call for fire using OFW CDAS was easier than sending a voice call for fire.
- The average for single mission times sent from a Soldier was 23 seconds from the sending of the call for fire to the time when the weapon system fired within the simulation environment, a dramatic improvement over current mission processing times for targets of opportunity: 2.5 minutes in Paladin Mission Training Plan.
- The OFW CDAS self-oriented map display was used extensively by all of the participants. This allowed the Soldier to navigate the urban complex where the experiment took place, with the map moving and rotating to account for the Soldier's direction of travel and location, and also showing friendly and enemy locations. All participants desired to have this capability in real world applications.

- Ease of use and rapid training are essential elements for success of any OFW system used by the dismounted Soldier. Based on the preliminary results of this experiment/demonstration, the OFW CDAS appears to be moving in the right direction concerning usability and training. Training could be accomplished in less than one hour, and for some individuals in less than 10 minutes.

Building / Enhancing Systems with C3Core Component Technology

There are many advantages to reusing existing C3Core component parts for developing systems. Figures 19 and 20 illustrate some of those advantages for TAH-RI development. CHI Systems currently (2004 Catalog in effect at start of Phase I) offers 33 separate C3Core component parts, against which the functional requirements for TAH-RI were matched to identify appropriate component parts that could be used to support this effort.

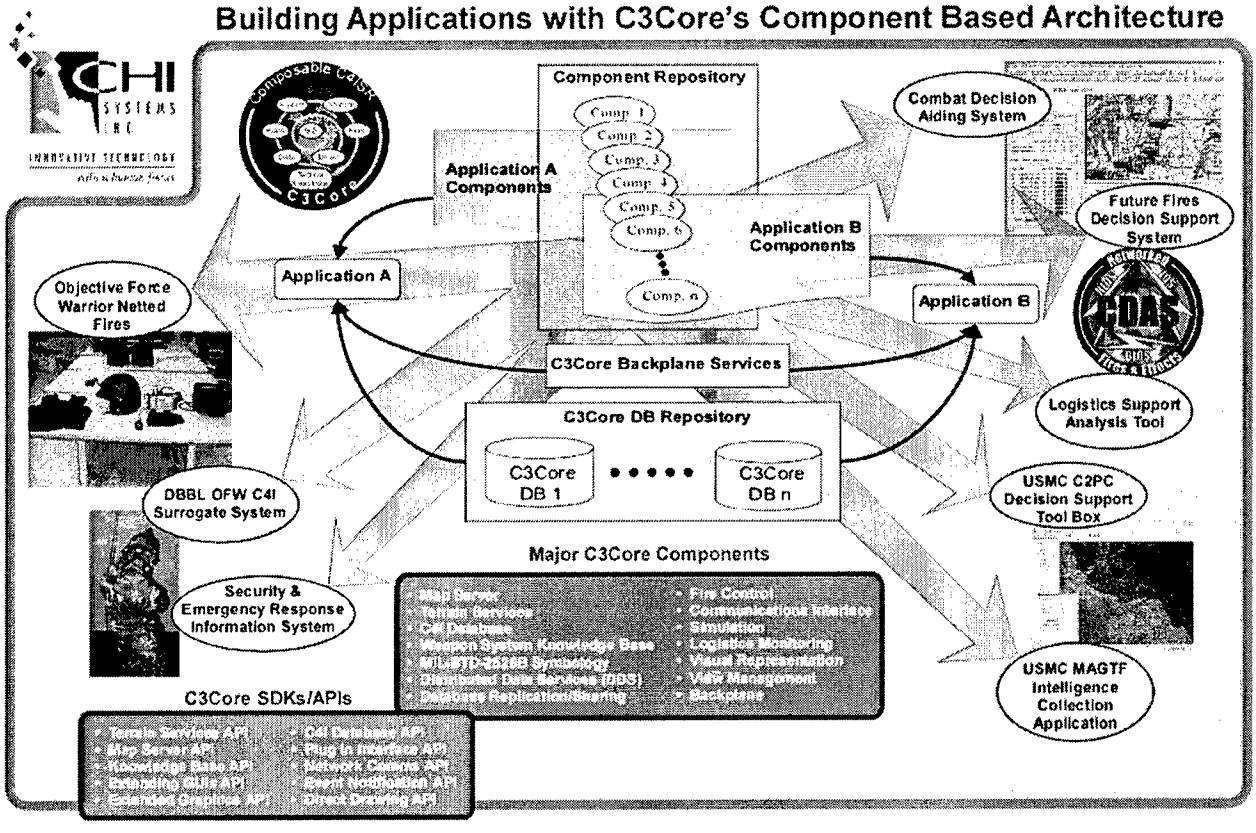


Figure 19. Why Build Applications with C3Core Components?

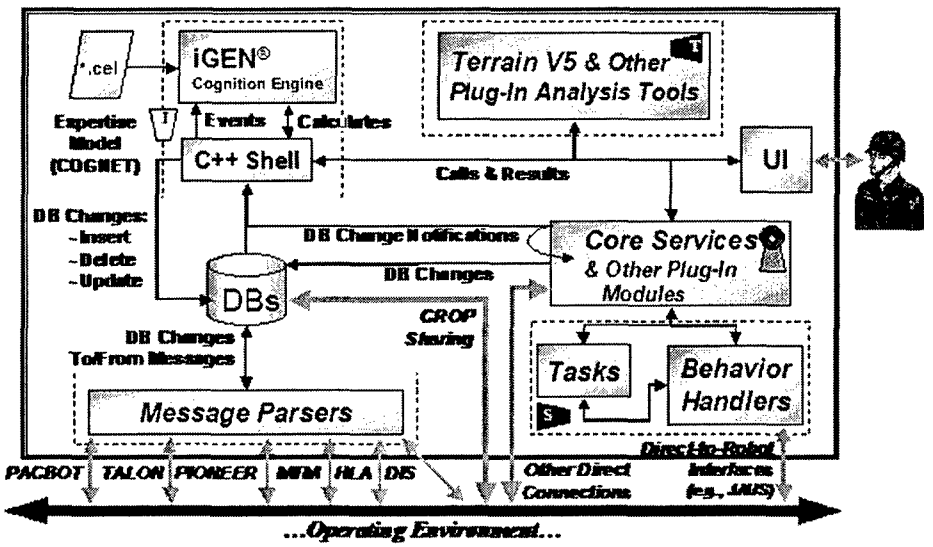


Figure 20. TAH-RI Architecture To Be Built With C3AF Components

The whole catalogue of C3Core components available when this Phase I effort began are described below in Table I, and pertain to a wide range of C4ISR-related capabilities, including: imagery, static data, dynamic data, terrain analysis, decision aiding, mobility analysis, input, planning, and situation awareness. It is expected that many of these components could be applied "as is" for Phase II development of TAH-RI and for enhancement of existing C2 digital tools with the TAH-RI sub-assembly. Other components may be modified and some requirements may not be represented in the current software suite. Technical requirements for these new components addressing unmet needs, will have to be assessed and the new components can then be designed and developed as soon as practicable (for TAH-RI development, this will be the principal focus of Phase II development). This will narrow the focus of the development effort to be conducted in Phase II largely to those unfilled requirements, which must be added to the C3Core component parts software collection. Each component comes with a detailed technical description, including Application Programmer Interface (API) documentation, and can be adapted as needed for the proposed systems' functional description.

Table I Reusable C3Core Software Components Based on C3AF (2004 Catalog)

Function	Description
Imagery	**ADRG Translator**. Extracts the raw data which is in an ADRG file format and produces data files in a tiled format suitable for mass storage. **Map Image Builder**. Provides the management capabilities required to build generic raster format map images. **Tactical Symbol Generator**. Provides the capability to produce MIL-STD-2525 unit symbology based upon Force Code, Echelon, Platform, and Organization.
Messaging	**Alert Log**. Provides a general service to allow for the collection, retrieval,

Table I Reusable C3Core Software Components Based on C3AF (2004 Catalog)	
Function	**Description**
(TAH-RI: HRI)	persistent storage and dissemination of alerts or user notifications. **E-Mail Component**. Provides e-mail based inter-operability between remote applications and is applicable through all domains and echelons
Static Data (TAH-RI)	**Unit Knowledge Base**. Provides fundamental properties of combat units, such as weapons systems, weapons ranges, and mobility speeds, for example. **DTED Manager**. The DTED manager component provides a simple interface to digital elevation data in NIMA's DTED format. **VPF Extractor**. Allows the extraction of data that is in the VPF (MIL-xxx) format.
Dynamic Data (TAH-RI)	**User Terrain Categorization**. Allows clients to describe terrain categorization in a collaborative fashion which can be used to overlay, augment or override terrain categorizations based upon static data. This is typically utilized to store transient terrain anomalies such as flooded terrain or contaminated areas. **Object Data Store**. Provides an easy to use API to allow for the definition and description of objects which are either planned or actual and can form the basis of an application's situational awareness.
Terrain Analysis (TAH-RI)	**DTED Categorization**. Produces a terrain categorization for unit mobility based either upon user defined parameters or default values for either a directional or non-directional analysis. **Cover & Concealment Evaluation (C&C)**. Provides either a cover or concealment evaluation upon a user defined area or point location using standard VITD data. **Generic Categorization**. Provides clients a high level abstraction above individual terrain analysis components and provides automated data fusion of these sub-components. This component is applicable within any environment when different types of terrain analysis must be performed and the results fused into a homogenous product for post processing or display. **Elevation Fusion**. Combines static DTED and VITD data together with user elevation data to produce composite elevation maps. **Line of Sight (LOS)**. Performs both point and area LOS calculations based either upon raw elevation data or composite elevation data based upon the Elevation Fusion component. **VITD Categorization**. Performs terrain categorization based upon VITD (Vector Interim Terrain Data) based upon three primary types of unit composition: Light Infantry, Armor/Mech and M1/M2. All terrain data for a given user defined area is passed through an extensive set of rules which categorizes the terrain into 5 different categories; Unrestricted, Restricted, Severely Restricted, Super Severely Restricted and Impossible.

Table I Reusable C3Core Software Components Based on C3AF (2004 Catalog)	
Function	**Description**
Other Decision Aiding	**Alerting Decision Aid**. Assists in the monitoring and management of cautions, warnings, and advisory messages from all decision aiding components in the weapon system. Currently, the ADA is intended to manage alerts from the following decision aiding systems: NBC; Maintenance; Logistics/sustainability; Self Protection; Route Planning; Battle Position Selection; and Planning. Other decision aids can be easily added. **Maintenance Decision Aid**. Assists in the monitoring of combat vehicle maintenance status, planning of scheduled and unscheduled maintenance, and performing emergency battle damage assessment and repair. **Logistics/Supportability Decision Aid**. Assists the user of the Artillery Decision Aid in planning of vehicle logistics resupply and shortfall prediction; and monitoring of the current vehicle logistics situation during combat operations. **NBC Defense Decision Aid (NBCDA)**. Assists the user in monitoring predicted and actual NBC conditions during combat operations, and to aid the user to develop passive and active defense and avoidance measures against NBC threats.
Mobility Analysis (TAH-RI)	**Mobility Corridors**. Identifies high speed mobility corridors though a piece of terrain. **Alternate Routes**. Fills the gap between optimal route selection and plausible route selection. A client specifies an area for analysis and many different useful calculations are performed to help identify or predict mobility behavior through terrain. **Mobility Range Analysis**. Produces different types of movement analysis through terrain. **Covered Routes**. Selects mobility routes through terrain which optimize both speed and coverage. **Position Selection**. Assists in the selection and evaluation of a firing location for either direct or indirect weapons platforms. **Route Distribution Model**. Determines high plausible area in the terrain which an object might travel. This form of calculation is extensively utilized for identification of Named Areas of Interest (NAI) and Targeted area of Interest (TAI), which can help in the development of Sensor Management plans and Fire Mission Plans. **Battle Position Selection**. Assists in the selection and evaluation of a firing location for either direct or indirect weapons platforms.
Input	**Eye Tracker**. Allows users to interact with the application using visual gestures as opposed to typical mouse control for hands free operation. When combined by a voice recognition component, this component allows true, hands-free operation of the computer's graphical user interface.

Table I Reusable C3Core Software Components Based on C3AF (2004 Catalog)	
Function	**Description**
Planning (TAH-RI: HRI)	**Mission Planner**. Allows clients to create, manipulate, disseminate and store a planning scenario or course of action. This can be effectively utilized for the generation of mission orders, war gaming or simulation during the planning process. During the execution phase of a mission the planning component can seamlessly integrate with situational awareness object store to provide the basis for alerting mechanisms or decision aids. **Static Plan Checker**. Associated with the Planning component to provide an automated means to validate plans prior to the development of mission orders. **Dynamic Plan Checker**. Provides plan validation in regards to feasibility and optimality, analyzing whether a plan is technically feasible within the client provided constraints.
Planning/ Situational Awareness (TAH-RI: HRI)	**Run Time Alerting**. Similar to both the Static and Dynamic Rule components though the rules are tailored towards detecting differences between the plan and the current situation. Three different rules are incorporated into this component, which categorize the type of alert based upon threat. **Synchronization Matrix**. Produces a time, space and action overview of a plan or operation which closely integrates within the IPB or situational awareness actions currently utilized in the military.
Process Control (TAH-RI)	**Event State Machine**. Provides an interface for 3rd party applications to become part of the control event loop such as a GUI environment.

In Phase II development, CHI Systems technical team will identify the intended hardware footprint(s) for the proposed system and ensure that the software to be adapted for TAH-RI is scaled to the anticipated footprint(s). Code profiling and rigid adherence to best practices for coding during implementation are the principal means of ensuring a good fit to the intended delivery platform. C3AF and most of the C3Core component software parts have been implemented on PDAs, notebook computers, and wearable computers. A few more complex components like the iGEN® Cognition Engine Plug-in tend to require a bit more computational power than available on current PDAs, although it has been employed extensively on notebook computers and other transportable or embeddable computers. The intent of this analysis is to determine the functionality that can be implemented on each proposed delivery platform. See the Discussion section of this report for more discussion of the various design and deployment tradeoffs made in our Phase I design for the TAH-RI sub-assembly.

Understanding the Cognitive Work Needed for Battlefield Decision Making

CHI Systems, and the proposed Principal Investigator in particular, has a long history of successful work in understanding the cognitive work needed for humans or intelligent agents to make decisions that are effective and timely. The COGNET framework has been hailed (Eggleston, 2004) as "...a fully developed [Cognitive Systems Engineering] framework..." CHI

Systems' prior work over the past two decades has resulted in development of a framework for representing context in the cognitive terms that people represent and maintain it. This framework is called COGNET (Zachary, Ryder, Ross, & Weiland, 1992), and incorporates a notation for capturing both the declarative and procedural knowledge of a work-domain ontology, including the expertise needed to generate expert-level behavior. Later, a software engine called BATON was built to allow COGNET context representations to be authored and directly translated into software (Zachary, Le Mentec, and Ryder, 1996). BATON, which can be thought of as an executable *cognition engine*, is one of several components forming a commercially available integrated toolkit, called iGEN®, for building cognitive model-based intelligent agents.

iGEN® -- The Cognitive Agent Software Development Toolkit

TAH-RI architecture incorporates the iGEN® Cognition Engine Plug-In component of C3Core, based on COGNET and the BATON executable cognitive architecture (see Pew & Mavor, 1998), although unlike most analogous systems it was created for engineering purposes (i.e., as a vehicle for creating practical applications) rather than as a platform for generating and/or testing psychological theory. Originally created as an engine to embed user-models into intelligent interfaces (Zachary, Ryder, Ross, & Weiland, 1992), the system has been generalized and extended over time to create a flexible framework for building cognitive agents for use in intelligent training, decision-support, and human performance modeling (see Zachary, Ryder, Santarelli, & Weiland, 2000). iGEN® is an integrated software development environment that supports the authoring, editing, debugging, and integrating of COGNET models (Zachary & LeMentec, 1999). Following is a brief summary of key facts about iGEN®:

- Toolkit for building intelligent software applications / interfaces
  - Stored expertise model representation of compiled human expertise enabling performance of a particular job / role – not a scenario-specific script
    - Build and maintain situation awareness (SA) in complex environments
    - Generate appropriate, competent behavior and attention-shifts
  - Integrated Development Environment (IDE) for authoring, debugging, testing, and reviewing (e.g., VV&A) expertise models
  - Runtime cognition engine based on human cognitive architecture, executes expertise model to generate timely expert-level behavior
- Theory-neutral, can build models implementing variety of different cognitive science theories (e.g., for memory; processes)
- iGEN® applications in situations where humans unavailable
  - Intelligent & distributed simulation (HLA compatible; synthetic team-mates)
  - Simulation-based training systems (instructors/tutors and student models)
  - Decision/performance support systems (embedded advisors, assistants)
  - Automation (intelligent agents; synthetic co-pilot/engineer)
- Agent-based Modeling and Behavior Representation (AMBR) program in which USAF (AFRL), with USN (ONR), evaluated competing architectures.

This patented COTS product will be used in TAH-RI (Figure 21) to provide higher-level expertise (1) to enable off-board or on-board mission planning for robots, and (2) to augment

robots' onboard navigation capabilities through integration of state of the art terrain analysis capabilities with awareness of the battlefield situation through a shared CROP and means of building and maintaining battlefield situation awareness for planning using the CROP, (3) to enable rapid deployment of reliable Intelligent Tutoring Systems for training human Soldiers in terrain understanding, and (4) to enable development of embedded performance support systems to help human Soldiers reliably operate at a higher level of expertise in integrating terrain understanding into their tactical behavior.

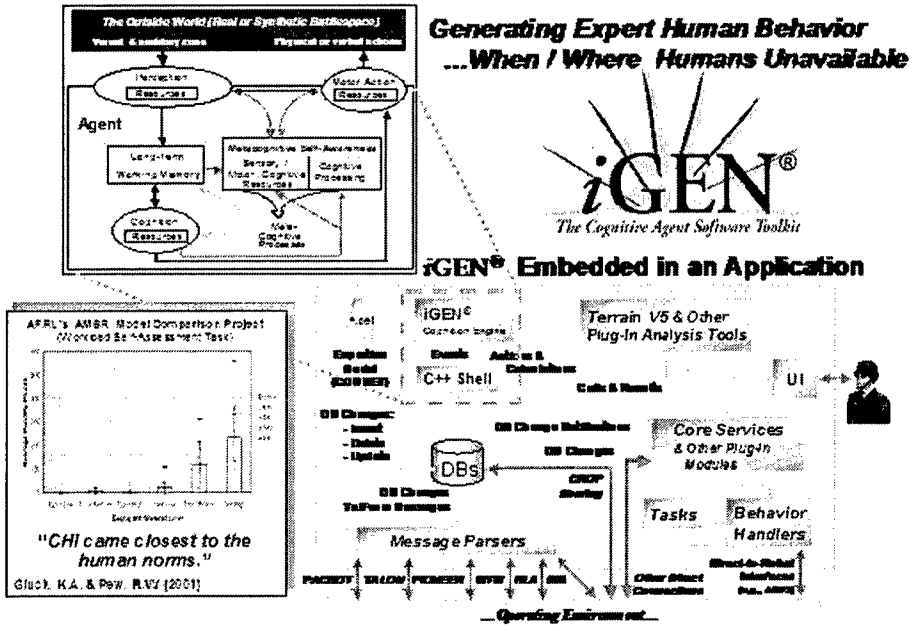


Figure 21. iGEN® Cognition Engine Plug-In Overview

COGNET was created as a general model which could be used for building specific models (or model instances) of human cognition and/or behavior for a range of specific purposes (which has grown over time). These purposes include design/analysis of person-machine interfaces and human work tasks, performance diagnosis in intelligent training systems, decision-support and performance-support in real-time computer-based work environments, and simulation of human behavior and performance, and now robot planning and higher-level behavior generation, a key purpose in this and other recent projects. As new COGNET model-instances have been built, a deliberate effort has been made to identify features that are common to most/all model instances and to retain these within the architecture, while maintaining customization affordances for more-detailed architectural features that may be needed (only) for certain types of model-instances. This process has been motivated by theory, ideally in the sense noted initially: to identify useful simplifying assumptions and boundary conditions of the known assumptions.

In specific, the COGNET cognitive architecture is based on the modified stage theory of human information processing. COGNET incorporates distinct but interdependent declarative and procedural knowledge representations. On the procedural side, it supports hierarchical goal/subgoal/operation procedural knowledge structures, integration of cognitive and behavioral operations, and context-sensitive modification of strategies based on declarative knowledge content. On the declarative side, it allows the notion of mental model, or other domain-specific

expert constructs to be incorporated. Attention management is an emergent property of the architecture and Principles of Operation, supporting multi-tasking easily and naturally. More recent COGNET developments provide metacognition mechanisms and allow a model to be aware of its own processes and states. This cognitive proprioception allows decision-making and performance to be modified based on the state of cognitive processing. These mechanisms were used in our ATC model to drive task load based strategies and error generation.

COGNET provides a surprisingly simple core architecture. Representations of process or structure limitations, such as memory capacity, decay, or recall constraints, visual regions and their acuity constraints, etc. are not included in the core architecture, although the iGEN® implementation is extensible and allows such representations to be added. The Principles of Operation that describe the functionality of the core architecture are derived from macro-theories of expertise, including Klein's recognition primed decision theory and Ericcson and Kintsch's long-term working memory model. As noted earlier, both here and in other applications COGNET/iGEN® has been able to produce highly realistic representations of human behavior in contexts as simple as the AMBR testbed or as complex as that of advanced Navy command and control. While some might suggest that the lack of such sub-process models makes COGNET/iGEN® a framework in search of a theory, the authors actually see the results as leading to a quite different conclusion. The lack of embedded theories of processing limits or other sub-processes makes COGNET/iGEN® a simpler and more parsimonious model than other models which incorporate these components, but has not prevented COGNET/iGEN® from producing high quality (and in many AMBR cases, the best-fitting) behavioral predictions. Thus, it can be concluded that for the purposes of human behavioral representation, such architectural features are not necessary and do not pass the test of Occam's razor.

COGNET does place substantial emphasis on the representation of knowledge, both procedural and declarative. It provides no standard or atomic level of representation, allowing adaptation to the modeling goal, but the representational forms, like the architectural Principles of Operation, are targeted toward the forms of expert knowledge typically used in generating skilled performance (rather than novice performance).

Distributed Field Robot Architecture (DFRA)

Figure 22 provides an overview of how autonomous robots make navigation decisions

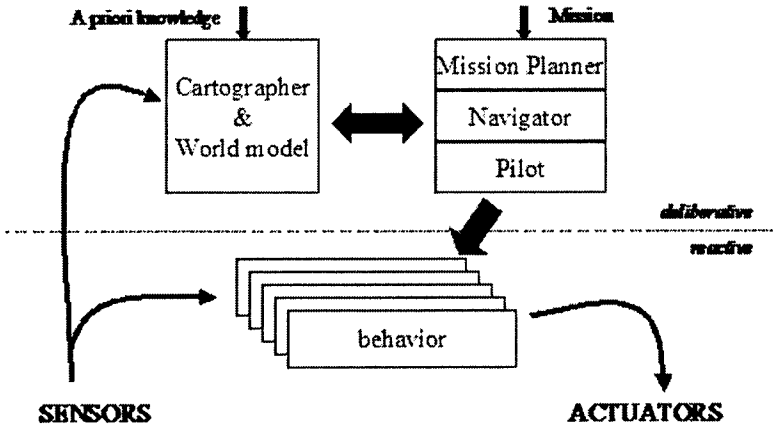


Figure 22. How Autonomous Robots Navigate

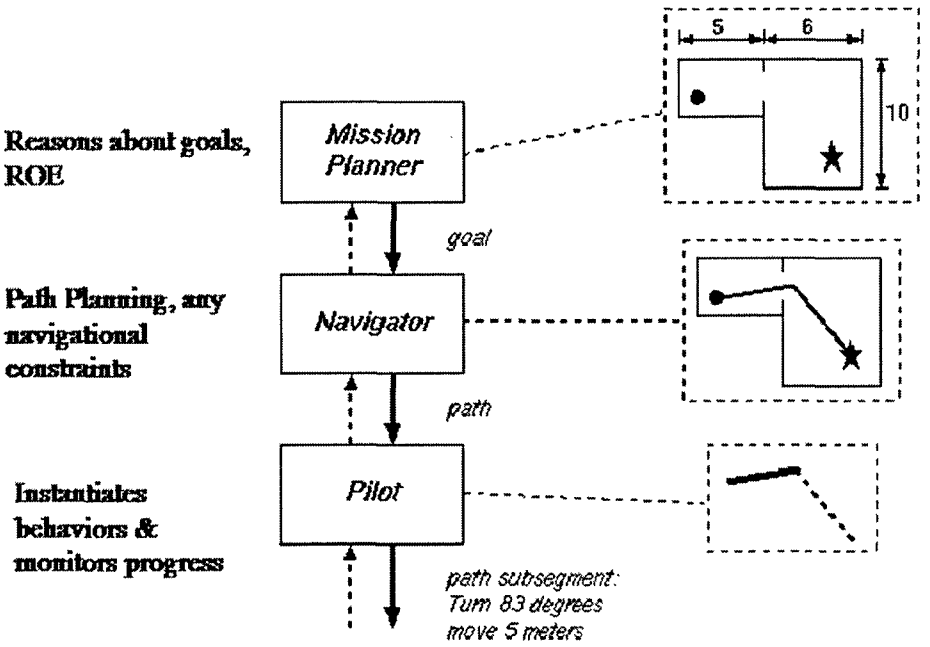


Figure 23. Nested Hierarchical Controller Approach to Path Planning / Navigation

and generate behavior sequences. Figure 23 illustrates how the nested hierarchical controller approach to path planning and navigation breaks down the situation into different scale problems, with the highest level problem description up at the Mission Planner level, mid-level path planning and consideration of navigational constraints considered as part of the problem description at the Navigator level, and the lowest-level details of behavior instantiation and monitoring of progress being tackled at the Pilot level. Figure 24 shows a simplified overview of the new TAH-RI plug-in, to be completed early in Phase II development using the Phase I implementation of the TRULLA algorithm onboard the designated robotic platform. Figure 25 illustrates the behavior-generation process from a robot's perspective, moving from sensed information on the left to actions taken on the right. Note that the decision-making needed to generate appropriate behavior at the actuator level is divided by roboticists into two different levels of behavior, the first called strategic behavior", but not tied to military tactical behavior deals with higher-level actions like "follow path", while the second level, called "tactical behavior" by roboticists deals with the lowest-level component actions (e.g., "speed-control", "avoid", "center-camera") implemented using available actuators on the robot. Figure 26 illustrates the Distributed Field Robot Architecture which integrates these elements into a more general robotic architecture.illustrates. Figure 26 illustrates the Distributed Field Robot Architecture which integrates these elements into a more general robotic architecture.

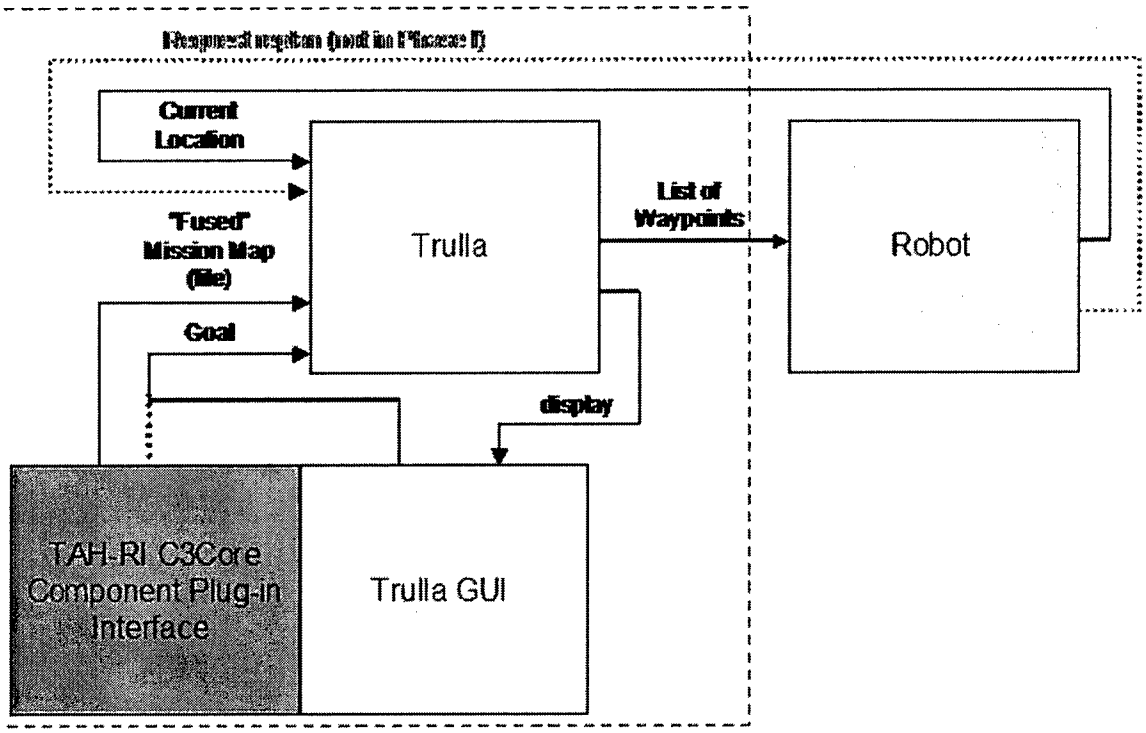


Figure 24. Simplified Overview of TAH-RI Trulla Plug-In Deployed On-Board Robot

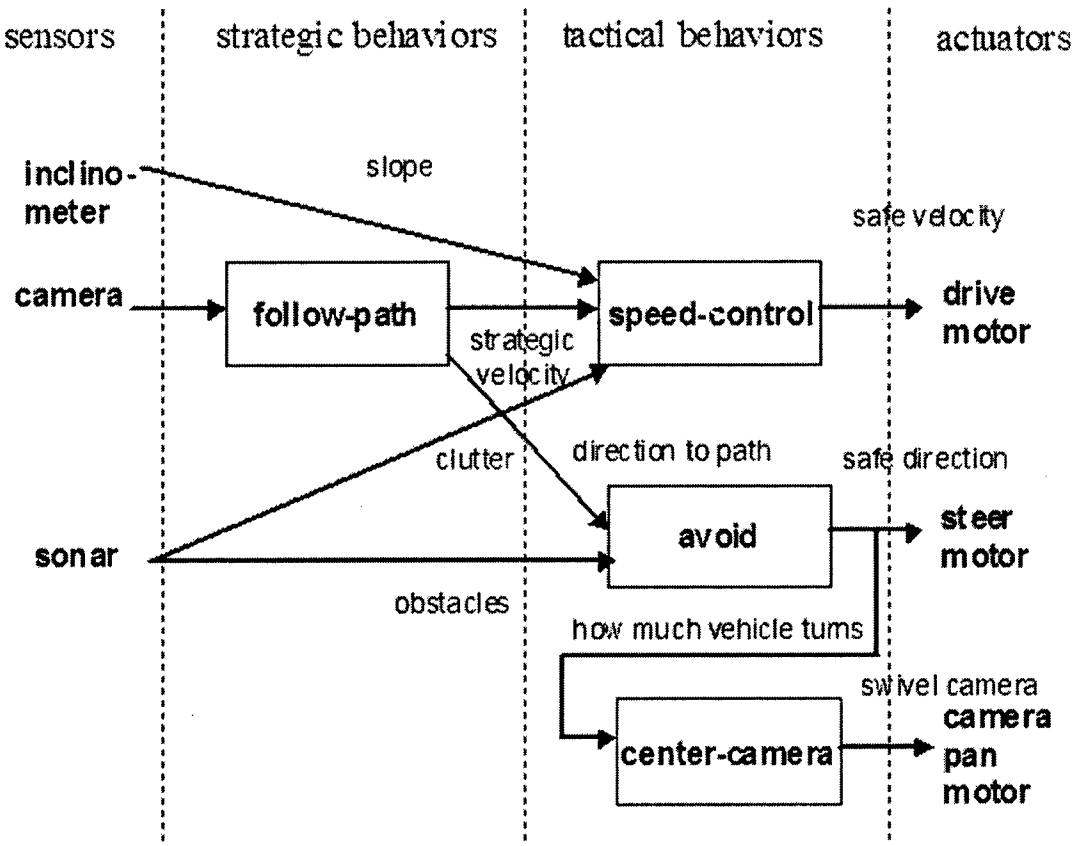


Figure 25. Behavior Generation from Robot Perspective

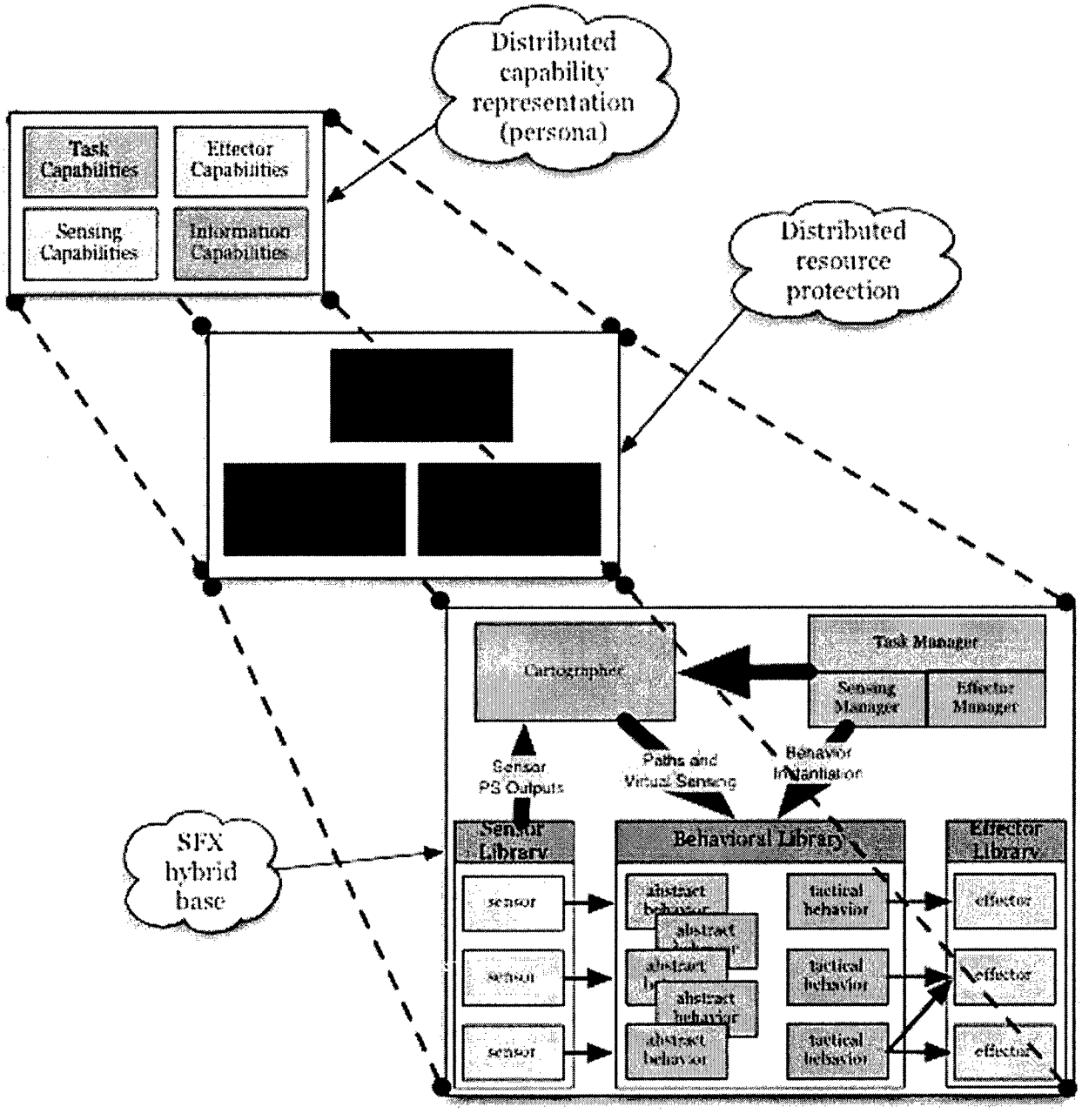


Figure 26. Distributed Field Robot Architecture (DFRA)

TAH-RI Architecture

The architecture for the TAH-RI sub-assembly to be implemented in Phase II is basically a combination of CHI Systems C3Core components with our iGEN® cognition engine plug-in, a set of tactical behaviors integrated with a simulation engine as the Sim9 Plug-In, and at least one new component to be built just for TAH-RI (illustrated in Figure 24, above) and one existing component (TERRAIN_V5/6) that will be significantly adapted for TAH-RI in a large portion of Phase II development with the addition of a large number of significant advances in storage, analysis, and spatial query-based retrieval of terrain features and tactical/operational elements of

the CROP. Figure 20, above, also illustrates the arrangement of these and other potentially useful components in the TAH-RI architecture. Figure 27, below, illustrates the value of this composable component-based approach (e.g., variety of delivery configurations possible) to the TAH-RI architecture.

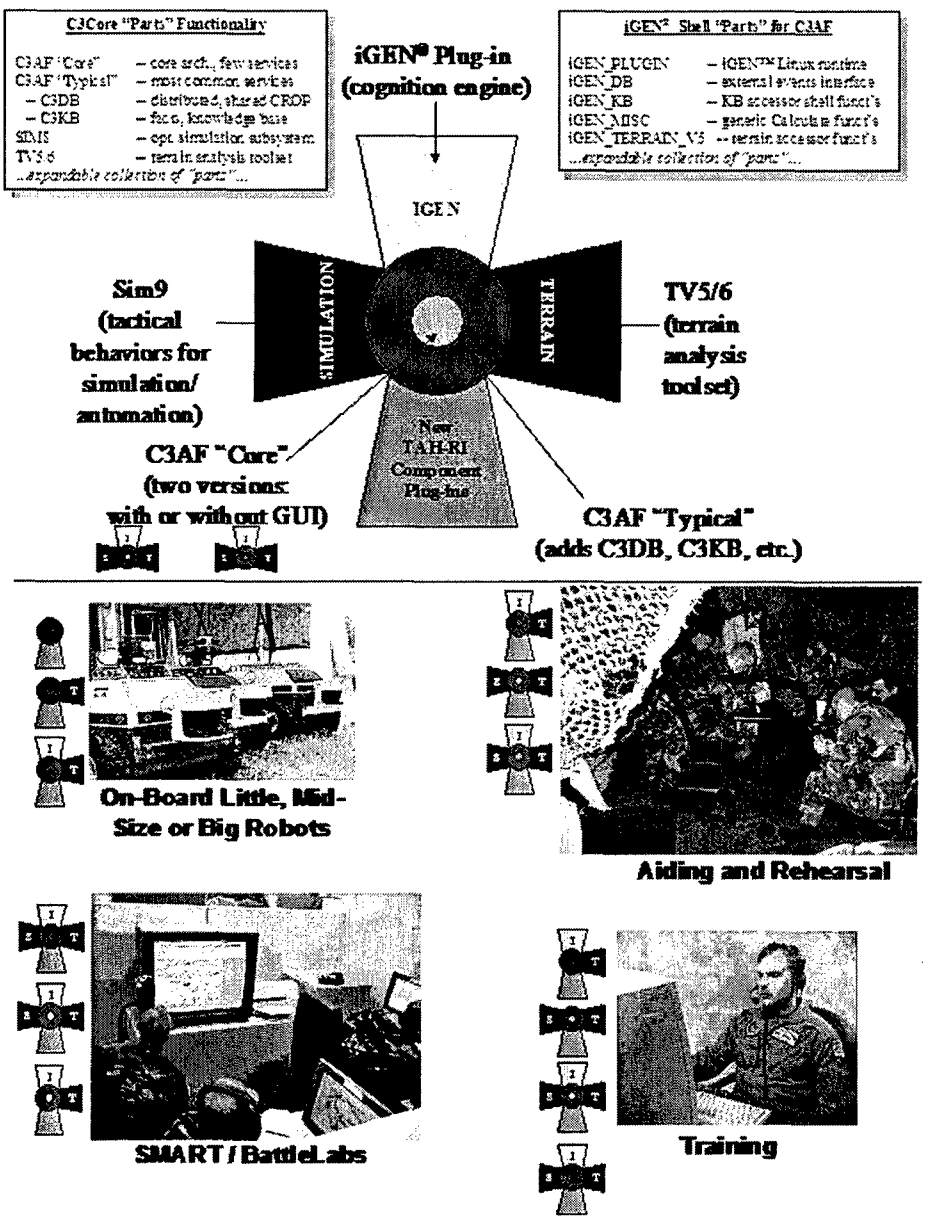


Figure 27. Conceptual Overview of Implications of TAH-RI Composable Architecture

Task 8 Results: Document Progress and Report Results.

This report constitutes the draft final report for this Phase I effort.

Discussion

In addition to the specific tasks described above, this Phase I effort also addressed several overarching issues which are discussed here. We start with the TAH-RI concept of operations (CONOPS), followed by a discussion of the many Human-Robot Interaction (HRI) issues relevant to TAH-RI design, development, and employment.

TAH-RI Concept of Operations

TAH-RI is intended to be a collection of software components integrated to work together as a sub-assembly within some larger system. For instance, TAH-RI could be used to help rapidly build a simulation-based Intelligent Tutoring System to improve readiness and ensure the highest level of competence among Soldiers preparing to deploy, who need to be able to integrate and apply terrain understanding with intelligence information and their CROP to guide their tactical behavior in situations where the terrain is complex and urban. In this case, TAH-RI already includes the iGEN® cognition engine, which has proven its value in training systems (Glenn et al, 2003; Zachary, Ryder, and Hicinbothom 1998; Zachary, et al, 1998; Zachary, Ryder, Hicinbothom, 2000), providing means of rapidly constructing synthetic team members (SYNTHERs) and synthetic instructors which call collaborate to assess student knowledge state in simulation-based Intelligent Tutoring Systems. The beginnings of an ITS could be constructed by combining TAH-RI with an appropriate Crew Station and underlying simulation (e.g., through OTB or other HLA/DIS external simulations, or even through the SIM9 component providing smaller-scale simulation capabilities appropriate for many ITS applications. The heart of the ITS, its assessment, record-keeping, and instructional intervention expertise could come from one of many Learning Management Systems and ITS development efforts within DoD, including DARPA's DARWARS system of systems for simulation-based training.

For robotics applications, TAH-RI could be used on a variety of robots, in several configurations, as illustrated in Figure 28, below. In this application, TAH-RI is utilized in three distinct configurations:

- First, as an integrated on-board cognitive agent system , $CA(SW)_A$ integrated with Robot A (HW/SW) through the new TAH-RI component illustrated in Figure 24.
- Second, as a stand-alone off-board cognitive agent system, $CA(SW)_B$ aboard a command vehicle or other C2 node. Note that in this configuration and the first, the TAH-RI cognitive agent would also listen to orders and information from the commander to the robot(s) so that, like good team members, they *overhear* essential information and help keep their situation awareness (SA) about their robots' status and plans and missions.
- Thirdly, as a small embedded component aboard Robot B (HW/SW) consisting primarily of the new TAH-RI component illustrated in Figure 24 along with the C3AF core and "typical" components in a sub-assembly needed to communicate with the distant commander, CO(Hum) and with $CA(SW)_B$ TAH-RI sub-assembly.

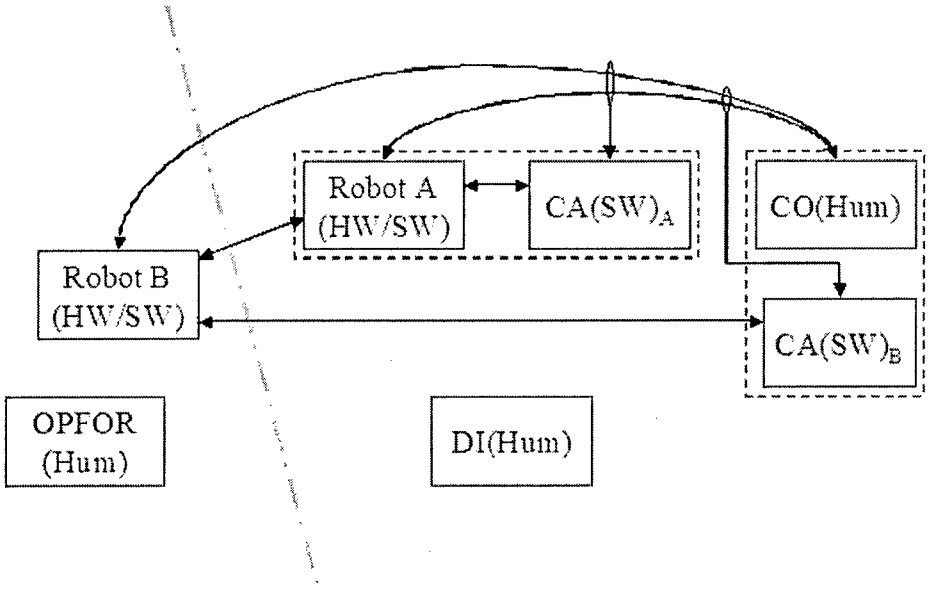


Figure 28. TAH-RI CONOPS for Autonomous Robotic Vehicles

Human-Robot Interaction with TAH-RI

Human robot interaction has traditionally addressed technical advances in robotics allowing for communication between human and robotic components of a system. With technological advances in communication, a recent shift to more human-centered HRI is underway. A series of workshops sponsored by DOE, the National Science Foundation, and Defense Advanced Research Project Agency (DARPA) has provided the impetus for much human-centered HRI work (DOE, 1998a; Murphy and Rogers, 2001).

HRI in the current context involves the active acquisition of information from robots, the transformation of that information into displays that help humans construct situation awareness, as well as into representations upon which the robot can similarly reason, and the network-based propagation of critical information in real time under communication failures and congestion. Figure 29 illustrates Human Robot interaction factors relevant to humans interacting with TAH-RI. Three dimensions are identified: the role of the human in the human-robot system, team design issues including the human to robot ratio and the proximity of team members, and levels of autonomy (Bruemmer, Marble, Dudenhoeffer, Anderson, & McKay, 2002).

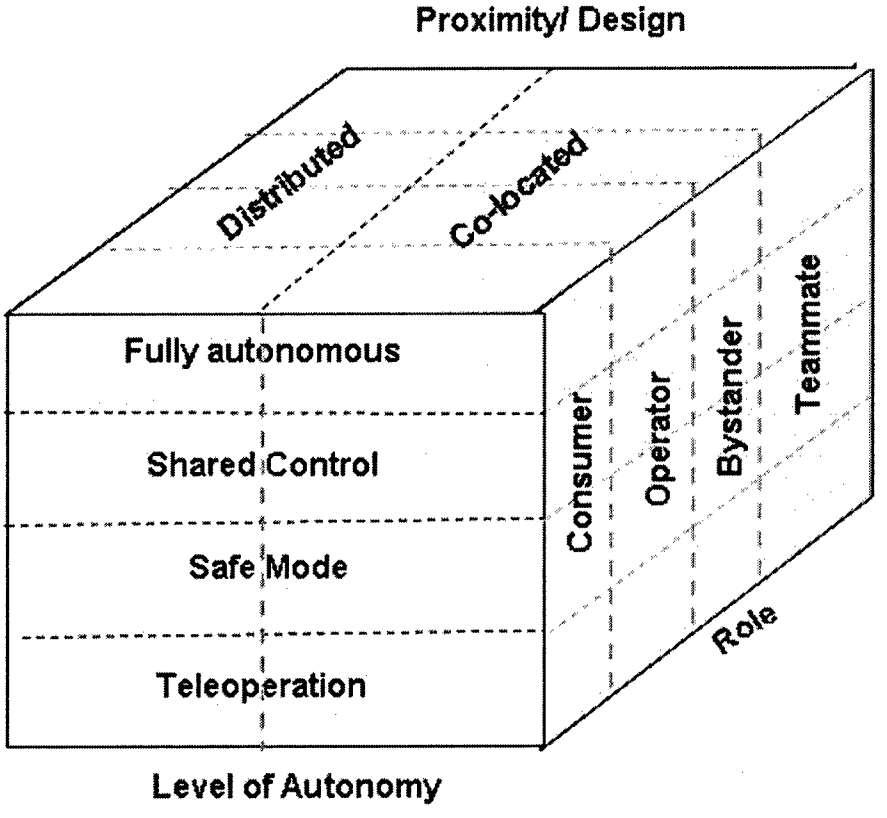


Figure 29. HRI considerations with TAH-RI

Human Role

Scholtz (2003) describes four human roles in human-robot osinteracting : ConsumerOperator, Bystander, and Teammate. Warfighters on the battlefield may find themselves in any one of these roles in interactions with TAH-RI:teammate.

- Consumer – Terrain data obtained from the robot will be utilized by humans (and other robots and intelligent agents and incorporated into mission planning and decision making processes. HRI must assess user needs and address graphical user interface requirements that support the understanding of commander's intent, and development of situation awareness (Endsley), while mitigating against the propensity toward cognitive overload. Identifying user requirements and supporting the interpretation of commander's intent and SA development during robot assisted task performance is a critical to effective human robot interaction with TAH-RI Operator – exhibiting varying degrees of human control over the robot based on the robot's level of autonomy. The human robot operator will always be in the loop; even autonomous robots will require significant human oversight and frequent intervention..

- Bystander- humans and robots tasks are independent of each other – the human may have little or no knowledge of the robot. Much of the existing human-robot interaction research has addressed the goals of social acceptance of robots or interface design, notably Breazeal, 2000; Arkin, Fujita, Takagi and Hasegawa, 2003; Draper, Pin, Rowe & Jansen, 1999; Wilkes, Alford, Cambron, Rogers, Peters & Kawamura, 1999; Khatib, Yokoi, Brock, Chang & Casal, 1999. Research suggests that people perceive autonomous robots differently than they do most other computer technologies. HRI with TAH-RI during terrain analysis in the field will necessarily require consideration of social behaviors; that is, human responses to and 'interpersonal'

interaction with, robots (e.g., issues trust, emotion, and attributions of being human-like). Implications of bystander interactions includes a requirement that the robot be able to communicate and explain it's goals, plans and actions to nearby humans.

- Teammate - humans and robots working collaboratively on tasks to accomplish shared goals. HRI with TAH-RI must be supported by providing both the human and the robot with information in usable formats. For the robot this means that information must be represented in a format that the robot can recognize, 'understand' and use. Given specific mission contexts, HRI becomes increasingly important, TAH-RI offers the robot within the human – robot system the ability to understand and reason about terrain, and to anticipate or tailor interactions with the human based on mission goals. In addition, especially in field applications, the robot will need assistance from the human to resolve uncertainties and to accomplish tasks. TAH-RI identifies underlying terrain features and offers some level of reasoning about those features. TAH-RI also provides common terrain referents to anchor human-robot interactions.

For example, UGVs must be able to navigate through the battlespace. Not only will robots help gather terrain data for interpretation and use by human team members, but the robot must also be able to recognize and interpret that terrain information available in terrain databases. Data providing shared referents for the development of 'common ground' are critical for coordinating human team activities (Kraut, Fussell, Brennan, & Siegel ; Olson & Olson, 2000). Human-robot teams will also be tasked with developing common ground – a common understanding of the situation based on objects or referents – in order to coordinate activities. (For example, once a terrain feature is identified, the human and robot can collectively reason about the implications of that feature for mission accomplishment.

Proximity

Autonomous robots are a distinctive case in HCI in that robots are mobile; resulting in differing levels of physical proximity with other robots, people, and objects. Proximity has an impact on the expected form of human robot interaction. Mobile robots will have to negotiate their interactions in a dynamic, sometimes physically challenging, environment (e.g. Burke, Murphy, Coovert, & Riddle, 2004; Yanco, Drury, & Scholtz, 2004). For example, humans may be interacting with the robot but be distributed from the robot (e.g., a human in a command post interacting with a robot in the field) and humans may also be co-located with the robot (e.g., Soldier walking along side a robot).

- Distributed - human-robot system, human robot interaction will likely focus on issues of human supervising, monitoring and controlling the robot, and issues related to acquiring, interpreting and integrating the terrain information obtained by the robot in order to develop appropriate situation awareness.
- Co-located - humans may be side by side with robots, engaged in independent tasks (e.g., reconnaissance) or they may be working collaboratively to accomplish a common goal. In the first case, working side by side with a robot, it is important to consider that people's perceptions of autonomous robots are often more anthropomorphic than their perceptions of other systems (Friedman, Kahn, & Hagman, 2003). In the second instance, working collaboratively on common tasks requires an understanding of team behaviors.

Human-Robot Team Configuration

In addition to proximity, specific team configuration also has implications for interacting with TAH-RI. Yanco & Drury (2002) describe a number of human- robot configurations based on the intersection of two dimensions – the ratio of people to humans and the level of shared interaction among teams: 1) one human controlling one robot, 2) one human controlling a group of robots, 3) one human controlling multiple independent robots (robots not coordinating amongst themselves), 4) a human team collaboratively issuing one command to one robot, 5) multiple humans controlling one robot, 6) a team of humans controlling a team of robots (collaborative), 7) teams of humans controlling multiple independent robots, and 8) multiple humans issuing commands to a robot team.

Currently, much of military HRI research is focused on single human operator supervision of either small groups of loosely coupled robots, or large groups of tightly coupled, autonomous robots (Young, Emmerman & Nguyen, 2002). As described in the introduction of this report, various attempts at controlling multiple robots in the field, requiring individualized user intervention, have failed.

Level of Autonomy

Across the battlefield robots exhibiting differing levels of autonomy and requiring varying levels of control. Bruemmer and Waldon's levels of autonomy support the various roles of the human in the human-robot team:

- Fully autonomous – the robot plans its own path, and responds to the environment requiring no input from the user except for high-level tasking.
- Shared control – robot has the initiative to plan its path and respond to the local environment. Robot queries human user for information and problem solutions.
- Safe Operations – the robot is controlled by the human user, however the robot can take safety initiatives. For example, in safe mode, if the robot senses an obstacle, and the operator navigates into that obstacle, the robot decides the command is not safe and will stop its movement to avoid collision.
- Teleoperation – the robot is continuously controlled, at a low level, by the human operator (except when communications drop out).

Mixed initiative HRI with TAH-RI requires robots and humans are able to 'understand' and predict each other's behavior (i.e., the robot has a model of human behavior and the human has a model of robot behavior). In interacting with TAH-HI, the system must also be able to recognize conditions in which human intervention is required, and when robot intervention is required and be capable of accepting variable levels and frequencies of intervention. For example, during path planning the commander may have directed the robot to follow roads or go through a particular checkpoint, but the main road may be blocked, and instead it needs to make up time by taking a short cut on a secondary road or trail. This requires it to relax a constraint, which generally requires permission from a higher cognitive agent (usually, the human). Additionally, robot must be able to explain why it is doing what it is doing to the human.

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